

NASA Technical Memorandum 89189

## Reports of Planetary Astronomy—1985

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# Reports of Planetary Astronomy—1985

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## FOREWORD

This publication is a compilation of summaries of reports written by Principal Investigators funded through the Planetary Astronomy Program of NASA's Solar System Exploration Division, Office of Space Science and Applications.

The summaries are designed to provide information about current scientific research projects conducted in the Planetary Astronomy Program and to facilitate communication and coordination among concerned scientists and interested non-scientists in universities, government, and industry.

The reports are published as they were submitted by the Principal Investigators and have not been edited.

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Office of Space Science and Applications

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## I. INNER PLANETS

N87-12408

THE ARECIBO S-BAND RADAR PROGRAM

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Co-Investigators: none

a. General Objectives: The high powered 12.6cm wavelength radar on the 1000-ft. Arecibo reflector is utilized for a number of solar system studies. Chief among these are: 1) Surface reflectivity mapping of Venus and Mercury. Resolutions achievable on Venus are less than 1.5km over some areas while those for Mercury are about 30km. 2) High time resolution ranging measurements to the surfaces of the terrestrial planets. These measurements, which have an accuracy of about 100m, are used to obtain height profiles and scattering parameters in the equatorial regions. By making measurements over several years they can also be used to test relativistic and gravitational theories by monitoring the rate of advance of the perihelion of the orbit of Mercury and placing limits on the stability of the gravitational "constant". 3) Measurements of the orbital parameters, figure, spin vector and surface properties of asteroids and comets. 4) Observations of the Jupiter and Saturn Systems when they are in view of the antenna.

b. Past Twelve Months: Reduction to images of the 1983 monostatic Venus mapping data was completed. Analysis of the images, including detailed comparisons with Pioneer Venus data and Soviet Venera 15/16 images, continued at Brown University and Arecibo. Feature locations in Arecibo Venus radar images produced between 1975 and 1983 were used to make a new determination of the rotation vector. This result is of general interest but was also required for planning and cartographic purposes for the Magellan mission. A new set of observations of Venus were made in March/April 1985, aimed at imaging low northern and high southern latitudes, including the south polar region, at 1 to 2km resolution. Technical problems with this data set have slowed its reduction to images. A limited number of ranging observations were made to Mercury and Venus with the aims described in a. Ten asteroids were detected increasing the number studied with the Arecibo system to almost 40. A system to allow high time resolution, as well as high Doppler frequency resolution, studies of small asteroids or comets which make close approaches to the earth has been implemented. A radar detection of Halley's Comet was obtained when it approached to within 0.62 AU of the earth in November/December of last year. It is still uncertain whether the echo is a reflection from the nucleus or from a cloud of cm-sized particles in the vicinity of the nucleus.

c. Next Twelve Months: A large effort will continue to be made to reduce the 1985 Venus mapping data to images. Analysis of these and the 1983 images will continue at Arecibo and Brown University including collaborative studies with the Soviet Venera 15/16 investigators. Additional refinements will be made in the determination of the rotation

vector of Venus. Further ranging measurements will be made to Mercury and Venus for the reasons given in a. The program to obtain radar imaging of the moon at resolutions between 150 and 300m will be resumed. These observations will simulate the performance of the Magellan radar mission to Venus and will be used to study the influence of incidence angle on interpretability. Eighteen asteroids will be observable over the next 18 months including 1980XB and 46 Hestia which are prime candidates for planned space missions. Any unexpected opportunities for cometary observations will be given high priority.

d. Relevant Recent Publications:

- "Dual-Polarization Radar Observations of Mars: Tharsis and Environs," Harmon, J.K. and Ostro, S.J., Icarus, 52, 171, 1982.
- "Radar Observations of Asteroid 1685 Toro," Ostro, S.J., Campbell, D.B. and Shapiro, I.I., Astron. J., 88, 565, 1983.
- "Identification of Banded Terrain in the Mountains of Ishtar Terra, Venus," Campbell, D.B., Head, J.W., Harmon, J.K. and Hine, A.A., Science, 221, 644, 1983.
- "Spectral Broadening of Planetary Radar Signals by the Solar Wind," Harmon, J.J. and Coles, W.A., Ap. J., 270, 748, 1983.
- "Venus: Volcanism and Rift Formation in Beta Regio," Campbell, D.B., Head, J.W., Harmon, J.K. and Hine, A.A., Science, 226, 167, 1984.
- "Radar and Photo-electric Observations of Asteroid 2100 Ra-Shalom," Ostro, S.J., Harris, A.W., Campbell, D.B., Shapiro, I.I. and Young, J.W., Icarus, 60, 391, 1984.
- "Radar Evidence of Cratering on Venus," Burns, B.A. and Campbell, D.B., J. Geophys. Res., 90, 3037, 1985.
- "Mainbelt Asteroids: Dual-Polarization Radar Observations," Ostro, S.J., Campbell, D.B. and Shapiro, I.I., submitted to Science, April 1985.
- "Mapping of the Southern Ishtar Terra Region and Characteristics of Selected Volcanic Structures on Venus," Stofan, E.R., thesis, Brown University, May 1985.
- "Geology of the Southern Ishtar Terra Region, Venus: Observations from Earth-bound Radar," Stofan, E.F., Head, J.W. and Campbell, D.B., submitted to J. Geophys. Res., June 1985.
- "Mercury Radar Altimetry: A Preliminary Analysis," Harmon, J.K., Campbell, D.B., Bindshadler, D.L., Head, J.W. and Shapiro, I.I., J. Geophys. Res., 91, 385, 1986.
- "Large Scale Horizontal Deformation in the Akna-Freyja Orogenic Belt of Ishtar Terra, Venus," Crumpler, L.S., Head, J.W. and Campbell, D.B., submitted to Geology, February 1986.

## GOLDSTONE SOLAR SYSTEM RADAR

Principal Investigator: Raymond F. Jurgens  
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Co-Investigators: Pamela E. Clark  
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 Martin A. Slade  
 Thomas W. Thompson  
 R. Stephen Saunders

a. OBJECTIVES: The primary objectives of this research are to provide information about physical nature planetary surfaces and their topography as well as dynamical properties such as orbits and spin states using ground based radar as a remote sensing tool. Accessible targets are the terrestrial planets: the earth's moon, Mercury, Venus and Mars, the outer planets rings and major moons, and many transient objects such as asteroids and comets. Data acquisition utilizes the unique facilities of the Goldstone Deep Space Network, occasionally the Arecibo radar, and proposed use of the VLA (very large array).

b. ACCOMPLISHMENTS: During the past two years, the major focus has been on reducing the backlog of data relative to Mercury, Venus, and Mars most of which was acquired prior to the beginning of the radar facilities upgrade in 1982. Recently, new data has been acquired for Venus, Mercury and Halley's comet.

The data processing facilities up-grade has been completed. This facility is based on a VAX 11/780 computer system coupled with a Floating Point Systems array processor. Virtually all of the original software written for the Xerox Sigma 5 computer has had to be converted for operation on the new computer system (roughly 150,000 lines of code). We estimate that the conversion is approximately 70% complete at this time. Data processing is progressing smoothly at this time. The laborious first step of translating to older seven track tapes to a more compact high density nine track format is under way for the data taken between 1980 and 1982. Processing of these tapes is scheduled to begin in April 86. The goal is to complete the processing of all the Venus data during FY'86. Priority has been placed on specific images and other data that support flight projects such as Pioneer Venus and Venus Radar Mapper. Currently, all Mercury data has been processed and new results are in publication.

c. PROPOSED RESEARCH: Radar observations of Mercury, Venus, Mars, Halley's comet and asteroid 1982 HR are scheduled for FY'86. Future plans call for observations of the Saturnian moon Titan and the Martian moons Phobos and Demos. Each of these experiments will yield data that either will be fully processed or partially processed under this work unit. Partially processed data are delivered to other user programs for completion or scientific analyses. The expected scientific output consists of the following for each target:

1. Mercury:

- a. New unambiguous images and topography of the imaged and unimaged portion of the planet.
- b. Data for ephemeris development and relativity experiments.

2. Venus:

- a. New high resolution images (1 km resolution) of specific areas.
- b. Data for improvements in the spin state determination.
- c. Data for future ephemeris development.

3. Mars:

- a. New topographic and surface roughness maps (extended coverage).
- B. Special X-Band observations for seasonal detection of subsurface water and ice.
- c. Data for ephemeris control.
- d. Detection and characterization of moons Phobos and Demos.

4. Jupiter:

- a. Characterization of the surface properties of the Galilean moons at X-Band.

5. Saturn:

- a. Surveillance of the ring scattering properties as a function of tilt angle. The objective is to determine a ring model that predicts both the radar and the Voyager radio science results.
- b. Detection of the moon Titan to determine the surface properties.



6. Asteroids and Comets:

- a. All accessible asteroids and comets will be studied with X-Band radar to determine surface properties, sizes, and spin states where possible.

Each of the above projects obtain data through a separately funded program operated by JPL's Tracking and Data Acquisition office using facilities of the DSN. Separate funding exists for scientific analysis of certain programs attached directly to mission goals, especially when outside investigators and co-investigators are involved. Raw radar data are processed into scientifically useful products with facilities supported by this work unit and are either analyzed internally or delivered to outside users. Separate proposals may be presented when data analyses are beyond the scope that can be covered by this work unit.

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Roth, L., Downs, G. S., Saunders, R.S., and Schubert, G., "Mars: Seasonally Variable Radar Reflectivity," LPS XVI, 1985.

Roth L., Saunders, R.S., and Thompson, T.W., "Radar Reflectivity of a Variable Dust Cover," Dust on Mars Workshop, p. 59, Arizona State University, Feb. 24-26, 1986.

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Thompson, T.W., Saunders, R.S. and Weissman, D.E., "Lunar and Venusian Radar Bright Rings," accepted for publication in THE MOON AND PLANETS.

RESEARCH IN PLANETARY ASTRONOMY

Principal Investigator: Thomas B. McCord  
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Co-Investigators: none

- a) PURPOSE: Determine the composition, structure and processes operating on the surfaces of solar system objects using the Mauna Kea observing facilities and modern instrumentation which was mostly developed by this group. Reflectance spectroscopy and multispectral imaging in the 0.3-5.0 $\mu$ m spectral region are the major techniques used. Of major importance has been the involvement of graduate students and young scientists in order to develop new people as well as new knowledge and techniques.
- b) PROGRESS: Major focus was in qualifying and using the new imaging spectrometer and the 2-D IR detectors for spectroscopy and imaging. Graduate students and several young new faculty were involved. The major observational program emphasis was on preparing for the next Mars opposition, and searching for compositional units in the lunar highlands.
- c) FUTURE: We will continue to use the new imaging spectrometer and the 2-D IR detectors for reflectance spectroscopy and imaging. Observational program emphasis will be on defining compositional units on Mars and in the lunar highlands. For Mars a search for carbonates in the 2.5-5.0 $\mu$ m region and for OH and H<sub>2</sub>O features will be emphasized. A search for circum-asteroid and star material will continue. Salts and H<sub>2</sub>O on Europa will be studied.

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- 11) Bell, J.F. and B.R. Hawke, "Lunar Dark-Haloed Impact Craters: Origin and Implications for Early Mare Volcanism," J. Geophys. Res., 89, 6899-6910 (1984).
- 12) McFadden, L.A., C.M. Pieters, R.L. Huguenin, B.R. Hawke, T.V.V. King, and M.J. Gaffey, "Reflectance Spectroscopy of Lunar Meteorite f/91197: Relation to Remote Sensing Data Bases of the Moon," Memoirs of the National Institute of Polar Research: Special Issue on Y/91197, in press (1986).
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- 15) Lucey, P.G., B.R. Hawke, T.B. McCord, C.M. Pieters, and J.W. Head, "A Compositional Study of the Aristarchus Region of the Moon Using Near-Infrared Reflectance Spectroscopy," Proc. Lunar Planet. Sci. Conf., 16th, in press (1986).

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- 1) Hawke, B.K., J.F. Bell, L.R. Gaddis, and P.G. Lucey, "Remote Sensing Studies of Endogenic and Exogenic Dark-Haloed Craters on the Moon."
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ADVANCED INFRARED ASTRONOMY

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Co-Investigators: Drake Deming, Fred Espenak,  
Theodor Kostiuk

Objective: The goals of this research include high resolution spectroscopic studies of planetary atmospheres and comets. Laser heterodyne and Fourier transform spectrometers are utilized in order to obtain high spectral and spatial resolution. This makes it possible to study localized, non-thermal, phenomena in low temperature and low density regions and to detect trace constituents. Ultrahigh spectral resolution and stability also enables the study of dynamical phenomena such as winds in planetary atmospheres, thermal tides, and the outflow of material in cometary comae.

Accomplishments: The CO<sub>2</sub> laser heterodyne spectrometer was used at the 3-m IRTF on Mauna Kea to make measurements of Mars during the 1984 opposition. Analysis of the observations of the mesospheric non-thermal emission demonstrated the existence of a warming of the Mars polar mesosphere, similar to the seasonal effects which are well known to occur at the Earth's mesopause.

A new laser heterodyne system was established at the McMath telescope on Kitt Peak. This system will be complimentary to the system at the IRTF, and will be used for observations of a more synoptic nature. A search for CO<sub>2</sub> and NH<sub>3</sub> on Comet Halley was done with the new Kitt Peak system (11/85) as well as with the IRTF heterodyne system (12/85, 4/86).

A Lamb-dip absorption cell was designed and constructed. Its use will allow extreme frequency stabilization of the laser local oscillator, which will greatly facilitate measurements of winds and dynamical phenomena. The Lamb-dip cell was used at Kitt Peak to study zonal and meridional winds in the atmosphere of Venus.

Water vapor was detected in Comet Halley using Fourier transform spectrometer on the Kuiper Airborne Observatory. The 2.65  $\mu\text{m}$   $\nu_2$  band was seen in emission, confirming non-thermal-equilibrium excitation models for comets.

A study was made of the variability of Jovian Ethane emission. The average volume mixing ratio of Ethane in the Jovian stratosphere was

found to be  $3 \times 10^{-6}$ , with the greatest variability seen in the auroral regions.

Proposed Research: Analysis of Fourier transform and laser heterodyne spectroscopic data will be completed, to determine the relative abundance of candidate parent molecular species ( $H_2O$ ,  $CO_2$ ,  $NH_3$ , etc.) and to refine radiative transfer and excitation models for cometary comae. Measurement of winds in the atmosphere of Venus will continue using Lamb-dip stabilized laser heterodyne spectroscopy. These wind measurements will be extended to the atmosphere of Mars during the 1986 opposition; this effort will provide scientific support for the forthcoming Mars Orbiter Mission. The nature of variability in the Jovian Ethane emission will be clarified by making observations at higher spatial resolution using the IRTF.

Figure: Example of laser heterodyne observations of an individual line in the  $\nu_9$  band of Ethane, seen in emission from the stratosphere of Jupiter. A model atmosphere fit to the data is also shown.

Publications: "Observations of the 10- $\mu$ m Natural Laser Emission from the Mesospheres of Mars and Venus", D. Deming, F. Espenak, D. Jennings, T. Kostiuik, M. J. Mumma and D. Zipoy (1983) Icarus 55, 347.

"Modeling of the 10- $\mu$ m Natural Laser Emission from the Mesospheres of Mars and Venus", D. Deming and M. J. Mumma (1983) Icarus 55, 356.

"Measurements of Stratospheric Ethane in the Jovian South Polar Region from Infrared Heterodyne Spectroscopy of the  $\nu_9$  Band Near 12 Microns", T. Kostiuik, M. J. Mumma, F. Espenak, D. Deming, D. E. Jennings, W. Maguire and D. Zipoy (1983) Astrophys. J. 265, 564.

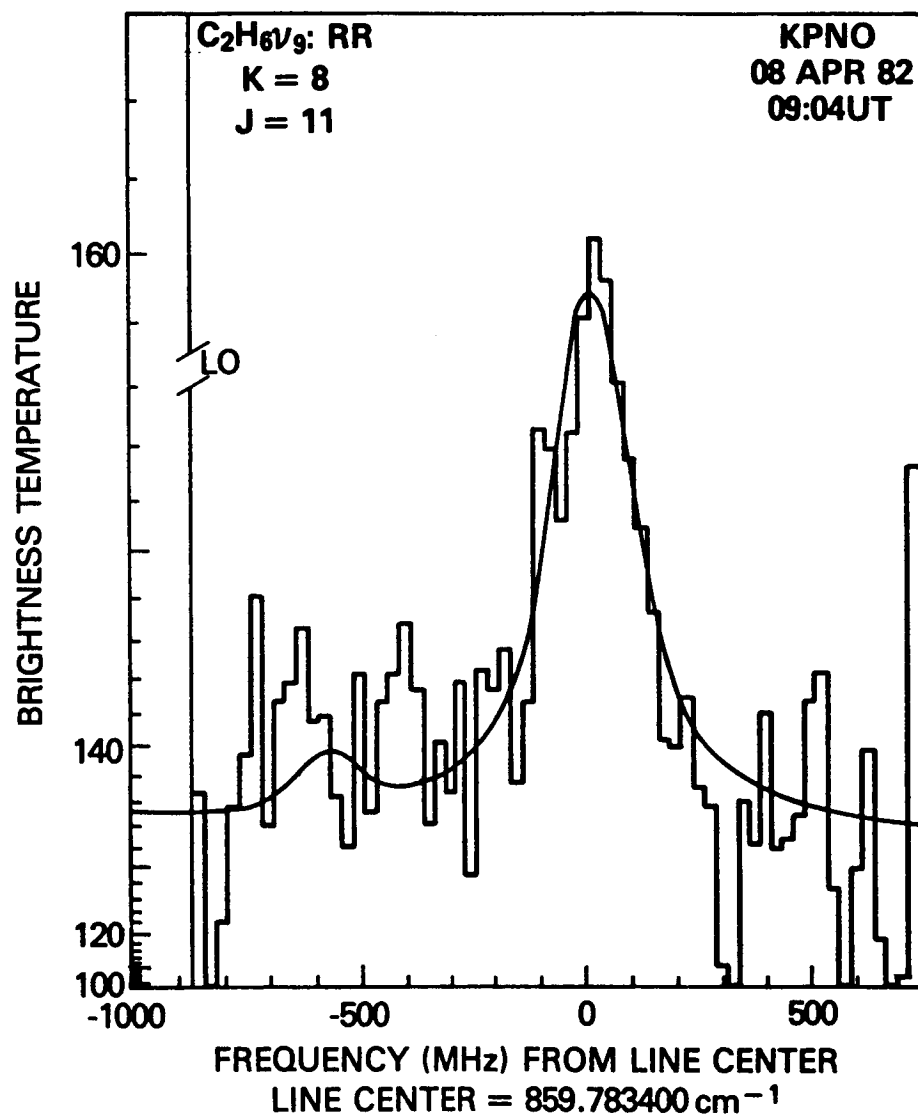
"Infrared Molecular Emissions from Comets", H. A. Weaver and M. J. Mumma (1984) Astrophys. J. 276, 782.

"Infrared Heterodyne Observations of Comet IRAS-Araki-Alcock (1983d)", H. A. Weaver, T. Kostiuik and M. J. Mumma (1985), submitted to Icarus.

"Polar Warming in the Middle Atmosphere of Mars", D. Deming, M. J. Mumma, F. Espenak, T. Kostiuik and D. Zipoy (1986) Icarus, to appear in the March 1986 issue.

"Detection of Water Vapor in Halley's Comet", M. J. Mumma, H. A. Weaver, H. P. Larson, D. S. Davis, and M. Williams (1986), submitted to Science.

JUPITER 60S CML = 336°



**II. OUTER PLANETS AND SATELLITES**

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LONG-TERM CHANGES IN REFLECTIVITY AND LARGER SCALE MOTIONS  
IN THE ATMOSPHERES OF JUPITER AND SATURN

Principal Investigator: Reta F. Beebe  
 Department of Astronomy  
 New Mexico State University  
 Las Cruces, New Mexico 88003

Co-Investigators: none

A. Objectives.

We are continuing a multi-color, broad-band photographic program for monitoring atmospheric variability of Jupiter and Saturn with the 61-cm, f/75 telescope at Tortugas Mountain. The archival product consists of approximately 20 sequential images on  $3\frac{1}{4} \times 4\frac{1}{4}$  glass plates with a plate scale of 4.53 arc sec/mm. An eleven-step sensitometric wedge, recorded times of acquisition, and fiducial marks which determine the orientation of the plate, are recorded on each individual plate. This allows accurate positional measurements, as well as detailed relative surface brightness determinations. This program has been systematically carried out since 1968, with blue images extending back to 1962, hence our archive now contains a systematic collection spanning almost two Jovian years and the major part of a Saturnian year. Acquisition, archiving, and analysis of the images and providing ephemerides and interpretation for other ground-based observers and space missions is the objective of this research.

B. Accomplishments.

1. Detailed measurements of the Red Spot are being utilized in a study of zonal velocity variation and our ability to predict the longitude of the Red Spot during the Galileo mission. If the longitudinal position of the Red Spot at opposition for the last 20 years is utilized to obtain a least squares fit of longitudinal versus time, the maximum deviation from the longitudes predicted by the equal-weight constant drift rate is less than  $\pm 30^\circ$ . The deviation from constant drift is a skewed sinusoidal function that appears to have a period of approximately 12 years. These predictions imply that the Red Spot should be decelerating toward the constant-drift base line. We will check this prediction during April and May. In addition, we are computing accumulated seasonal heating under assumed cooling rate models and comparing the seasonal heating with the longitudinal drift of the Red Spot.

2. An ongoing 5-color series of Saturn has been maintained this apparition. The purpose of this monitoring is to map the seasonal changes in the belt-zone reflectivity.

3. Digitization of a series of blue images containing the Red Spot and a series of red and blue images excluding the Red Spot are being processed and reduced to normalized surface brightness maps. This data is being utilized to map time-dependent brightness variations of selected features, belts, and zones.

**C. Proposed Research.**

We are proposing to maintain the ongoing collection of our standardized data base and to integrate these historical records with high resolution Voyager data in an effort to understand the long-term variations in the atmospheres of Jupiter and Saturn. In addition, we will continue mapping large scale features (white ovals, Red Spot, barges, etc.) to provide a continuous time-line to aid in planning HST and Galileo observations.

**D. PUBLICATIONS**

**1. Journals**

a. Beebe, R.F., R.M. Suggs and T.Little, Seasonal North-South Asymmetry In Solar Radiation Incident on Jupiter's Atmosphere. Icarus, In Press.

b. Beebe, R.F. and T.A.Hockey, A Comparison of Red Spots in the Atmosphere of Jupiter. Submitted to Icarus.

**2. Theses**

a. T.A. Hockey, Ground-Based Jovian Surface Photometry: 1968-1984, Master's Thesis, August 1985.

PLANETARY SPECTROSCOPY

Principal Investigator: J. T. Bergstralh  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: none

- a. The goal of this task is to acquire spectroscopic and spectrophotometric data on the atmospheres of comets, the outer planets, and Titan at ultraviolet to near-infrared wavelengths (approximately 0.2-2.5  $\mu\text{m}$ ). These data support an effort aimed at characterizing the physical properties and distribution of aerosol particles in the atmospheres of these bodies. This task supports only data acquisition and reduction; modeling is performed under task 154-30-80-10-55.
- b. Organized and conducted workshop on Earth-orbital Planetary Astronomy; report in preparation (collaboration with M. J. S. Belton, NOAO). Acquired new spectrophotometry of Uranus at  $0.2 < \lambda < 0.3 \mu\text{m}$  with IUE; acquired and recalibrated archival IUE spectrophotometry of Uranus and Neptune in this wavelength range. Published new estimates of radiometric Bond albedos and global energy budgets of Uranus, Neptune and Titan (separate collaborations with J. Neff, Univ. of Iowa, and J. Pollack, ARC). Under separate funding, published model of Uranus aerosol properties derived from data acquired under this task (collaboration with K. Baines, JPL). Participated in spatially-resolved photometric observations of P/Halley using IHW standard filter set and new CCD camera at JPL Table Mountain Observatory (collaboration with J. Trauger, JPL). Awarded observing time at McDonald Observatory, Mt. Palomar Observatory, and IUE per objectives for FY'86: These observing runs have not taken place as of the time of this writing.
- c. Objectives for FY'87 include (1) organize, conduct, and edit proceedings of Uranus symposium (collaboration with M. Matthews, Univ. of Arizona), (2) spectrophotometry of Uranus and Neptune with HST High Resolution Spectrograph, if launched, to acquire quantitative data on Raman scattering by molecular hydrogen.
- d. Three refereed journal articles (Icarus); two abstracts (DPS).

SEARCH FOR VOLATILES IN THE SURFACES OF ICY SATELLITES

Principal Investigator: R. H. Brown  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

Co-Investigators: none

OBJECTIVE: It is proposed to measure the reflectance spectra of the icy satellites of Jupiter, Saturn and Uranus in the spectral region 1.8 to 2.4  $\mu\text{m}$ . These observations would use the new Cooled Grating Array Spectrometer using a 32-element InSb photodiode array detector (the spectrometer was constructed by Alan Lokunaga of the IRTF at Mauna Kea Observatory) and will produce spectra of higher resolution and precision than any data yet obtained; the ultimate scientific objective is to search for the signatures of methane clathrate, ammonium hydroxide or carbon monoxide clathrate--compounds predicted to exist on icy surfaces in the outer solar system by several theories of formation of these bodies--in the region of the spectrum where water ice has a relative maximum in reflectance. At the very least, these data will allow upper limits to be placed on the amount of these chemical species that can be present. The specific targets this year will be Europa, Ganymede, Enceladus, Ariel and Titania, bodies that have the highest probability of having some or all of these volatiles on their surface according to current formation models.

PROGRESS: At present the PI has obtained important new data on Jupiter's satellite Europa, and preliminary analysis of the data shows the presence of ammonia hydrate or magnetospherically implanted sulfur exists on the trailing side of Europa. If further observations confirm the tentative suggestion of ammonia hydrate, these observations will be the first to demonstrate the presence of ammonia on any solid surface in the outer solar system.

PROPOSED WORK: This year it is proposed to continue to observe Europa and Ganymede in the Jovian system, Enceladus and Dione in the Saturnian system, Ariel, Titania and Umbriel in the Uranian system and Neptune's satellite Triton. These objects are considered the most likely to have some or all of the aforementioned volatiles on their surfaces and will be the highest priority targets. Nevertheless, it is important to extend this study to all the icy satellites in the Jovian, Saturnian, Uranian, and Neptunian systems and that will be the subject for the year following this year.  
2 abstracts, 2 papers, 2 presentations.

## THEORETICAL AND OBSERVATIONAL PLANETARY PHYSICS

Principal Investigator: John Caldwell  
 Earth and Space Science Department  
 State University of New York  
 Stony Brook, NY 11794-2100

Co-Investigators: R. Halthore

**ABSTRACT:** a.) OBJECTIVES The goal of this program is to support NASA's deep space exploration missions, particularly those to the outer Solar System, and also to support NASA's Earth-orbital astronomy missions, using ground-based observations, primarily with the NASA IRTF at Mauna Kea, Hawaii, and also with such instruments as the Kitt Peak 4 meter Mayall telescope and the NRAO VLA facility in Socorro, New Mexico. An important component of the program is the physical interpretation of the observations. The justification of this work is that it is possible to complement the mission science by extending observations in the temporal and spectral domains beyond what the missions can do. One example, which is illustrated below, is the monitoring of Jupiter at  $8\ \mu\text{m}$  wavelength, which corresponds to the  $\nu_4$  fundamental band of methane. Because of the high opacity in this band, Jovian radiation there originates above the 10 mbar pressure level in the stratosphere. It is a wavelength that Galileo cannot observe. Continuing observations at this wavelength since 1979 under this program will provide essentially one complete Jovian seasonal coverage at stratospheric altitudes between the Voyager and Galileo epochs. This wavelength is highlighted here because several significant discoveries have been made at  $8\ \mu\text{m}$ . These are illustrated below. Other wavelengths near  $20\ \mu\text{m}$ , which sample the troposphere, have also been monitored for seasonal variations.

b). ACCOMPLISHMENTS Within the limited resources of this program, it has been a major milestone to develop the observational techniques and the data reduction software to change from the earlier one dimensional planetary scans, usually from north to south along the planetary central meridian, to two dimensional raster-scanned images.

There have been two major scientific discoveries resulting from  $8\ \mu\text{m}$  observations of Jupiter. The first is that at that wavelength there are two spots, one near each magnetic pole, which are typically the brightest and therefore warmest places on the planet. The effect is clearly due to precipitating high energy magnetospheric particles. Recently,  $8\ \mu\text{m}$  images have confirmed that the north polar spot is fixed at System III coordinates ( $180^\circ$ ,  $+60^\circ$ ) but that the south polar spot moves in longitude between  $270^\circ$  and  $90^\circ$ . When followed for several hours, the south polar spot is observed to move toward increasing longitude. It has never been seen between  $90^\circ$  and  $270^\circ$ . (An interesting consequence of this research is that an examination of Voyager data, at the location of the north polar spot determined from ground-based work, revealed a "pre-discovery" hot spot observation, and the Voyager infrared spectra showed that the polar chemistry is significantly different from that at the equator).

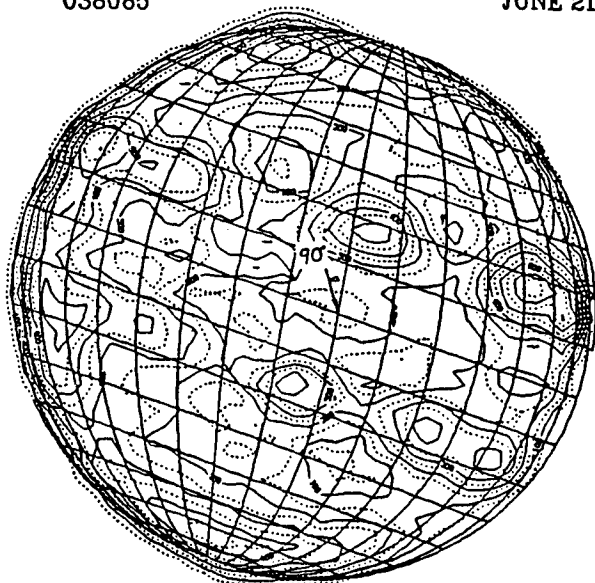
A second ground-based discovery is that in 1985, Jupiter exhibited low latitude ( $\pm 18^\circ$ ) stratospheric wave structure. See the figures. Such structure was either absent or had a much lower amplitude in earlier years.

c). PROPOSED RESEARCH Work will continue at the IRTF to monitor the south polar hot spot motion, in order to understand its systematic properties. The nature of the low-latitude waves will be further investigated. An initial interpretation

in terms of Rossby waves has been developed. If they are still present in 1986, they will be reobserved. A major new effort will be made to detect Jovian aurorae near  $2\text{ }\mu\text{m}$  in the  $\text{H}_2$  fundamental vibration band. This will fill in the spectral gap between the well known  $\text{H}_2$  ultraviolet aurora and the  $8\text{ }\mu\text{m}$  features previously observed. An effort will be made to confirm an unpublished VLA measurement that indicated major hemispheric asymmetry in Titan's microwave emission. If the asymmetry is confirmed, the interpretation probably would be that the surface has major hemispheric compositional differences, with different emissivities. The result needs confirmation because the calibrator used initially was subsequently found to be variable.

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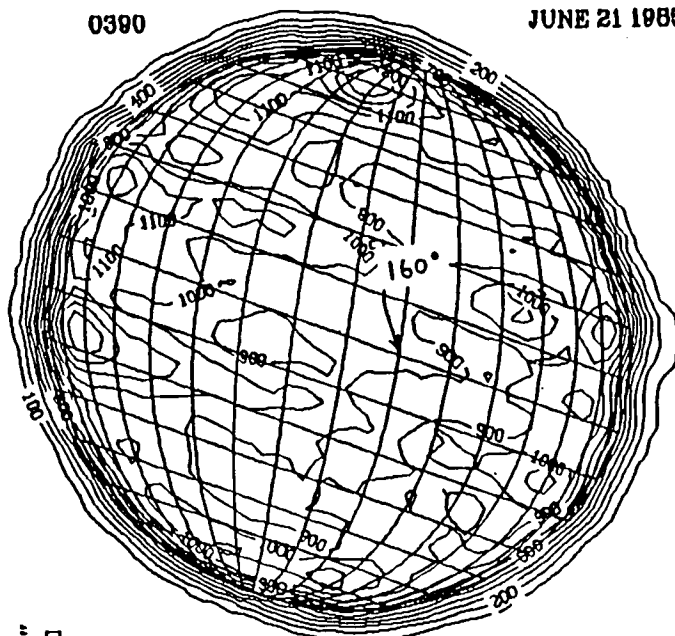


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Figure 1. An  $8\text{ }\mu\text{m}$  raster image of Jupiter, showing wave structure at mid-latitudes and a polar hot-spot about to rotate onto the disk from the north-east (upper-left) limb.

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Figure 2. A similar image later in the day, when the northern hot spot has rotated close to the central meridian. In both figures, radiation originates in the Jovian stratosphere or higher.

PORTABLE HIGH SPEED PHOTOMETRY SYSTEMS FOR  
OBSERVING OCCULTATIONS

Principal Investigator: James L. Elliot  
Department of Earth, Atmospheric and  
Planetary Sciences  
Massachusetts Institute of Technology  
Cambridge, MA 02139

Co-Investigators: Edward W. Dunham

**a. Objectives:** Because of their high spatial resolution, stellar occultations have proven extremely effective for learning about planetary upper atmospheres, asteroids, and planetary rings. Our ring orbit studies for Uranus have been particularly fruitful because we have been able--through occultations--to obtain data of high spatial resolution ( $\sim 2$  km) at the rate of 1-2 times per year. Our occultation program at M.I.T. involves (i) identifying the scientific questions that can be answered by occultation events, (ii) predicting the zone of visibility for the useful events, (iii) maintaining and improving a set of portable high-speed photometric systems, (iv) obtaining the observations, and (v) reducing the data and interpreting the results.

**b.1.** Two stellar occultations by Uranus occurred in May 1985, and we observed them with a network of large telescopes that encompassed the northern and southern hemispheres. Portable quartz-oscillator time standards were used at all observatories, and were calibrated before and after each event. High time-resolution data, accurate absolute time standards, and the large north-south baseline make these observations especially valuable for refinement of the orbits of the rings. Observations obtained from Cerro Tololo and McDonald Observatories of the 4 May and 24 May 1985 occultations by the Uranian rings clearly show a companion to the delta ring on both the immersion and emersion traces. It lies adjacent to the inside edge of the delta ring and has a width of about 10 km and an observed optical depth of 0.04, with significant variations from profile to profile.

**b.2.** We observed the occultation by Ceres that occurred on 12 November 1984, and submitted our data to R.L. Millis, at the Lowell Observatory, who is using all available Ceres occultation data in a collaborative analysis. Preliminary results give a mean diameter of  $933 \pm 10$  km, which implies a geometric albedo,  $P_v = 0.07 \pm 0.01$  and a density  $2.7 \pm 0.3$  gm cm $^{-3}$ . Hence Ceres is likely composed of silicate material throughout.

**b.3.** This past year we devoted our efforts in this area to obtaining photometry of stars to be occulted by Uranus, Neptune, and Pluto - as predicted by Mink and Klemola (1985) - in order to determine the most valuable events to observe. Our analysis of this photometry is complete and three papers have been submitted to *Icarus* (see Section 4).

**c.** We shall continue analysis of the high-quality Uranian rings occultation data that we obtained last spring, and we expect to achieve the following goals: (i) the precision of our ring precession rates should improve by a factor of 20, which would make our orbit model sensitive to an icy shepherd satellite with a diameter of 8 km that was 100 km distant from a ring; (ii) the precision of our values for the harmonic coefficients of the Uranian gravity field,  $J_2$  and  $J_4$ , should also improve by a factor of 20, and (iii) the improved reference system for the ring orbits should also allow us to obtain a considerably more accurate value for the planetary oblateness of the Uranian upper atmosphere that we have determined from our observations of previous planetary occultations. These improvements in our understanding of the Uranian system will be particularly timely in view of the Voyager encounter of Uranus that occurred during January 1986.

#### 4.d Publications

##### 1984

"Results from the Occultation of 14 Piscium by (51) Nemausa," by E.W. Dunham, R.L. Baron, S. Conner, D.W. Dunham, J.B. Dunham, G. Schneider, H.L. Cohen, V.T. Helms III, M. Croom, and Sefko, *Astronomical Journal*, **89**, 1755 (1984).

"Structure of the Uranian Rings. I. Square-Well Model and Particle-Size Constraints," by J.L. Elliot, R.G. French, K.J. Meech, and J.H. Elias, *Astronomical Journal*, **89**, 1587 (1984).

"The Structure of the Uranian Rings and The Search for Rings Around Neptune," by J.L. Elliot, in *Uranus and Neptune*, J.T. Bergstrahl, Ed., U.S. Government Printing Office, 1984-739-010/27.

"Oblateness of Uranus and Neptune," by R.G. French, in *Uranus and Neptune*, J.T. Bergstrahl, Ed., U.S. Government Printing Office, 1984-739-010/27.

##### 1985

"The Rings of Uranus," by J.L. Elliot and P.D. Nicholson, in *Planetary Rings*, R. Greenberg and A. Brahic, Eds., University of Arizona Press, 1985.

"Photometry of Occultation Candidate Stars. I. Uranus 1985 and Saturn 1985-1991," by L.M. French, G. Morales, A.S. Dalton, J.J. Klovett and S.R. Conner, *Astronomical Journal*, **90**, #4, 668 (1985).

"Predicted Occultations by Uranus, Neptune and Pluto: 1985-1990," by D.J. Mink, and A. Klemola, *Astronomical Journal*, **90**, #9, 1894 (1985).

"The 1983 June 15 Occultation by Neptune. I. Limits on a Possible Ring System," by J.L. Elliot, et al., *Astronomical Journal*, **90**, #12, 2615 (1985).

"The 1983 June 15 Occultation by Neptune. II. The Oblateness of Neptune," by R.G. French, et al., *Astronomical Journal*, **90**, #12, 2624 (1985).

##### 1986

"JHK Magnitudes of Occultation Candidate Stars: Neptune 1986-1990, Uranus 1987-1990, and Pluto 1986," by C.E. Covault and L.M. French, *Icarus*, (in press).

"Magnitudes of Pluto Occultation Candidate Stars", by A.S. Bosh, J.L. Elliot, S.E. Kruse, R.L. Baron, E.W. Dunham, and L.M. French, *Icarus*, (in press).

"Photometry of Occultation Candidate Stars. II. Uranus 1985-1990 and Saturn 1986-1991," by L.M. French, G. Morales, S.L. Gaiser, and J.A. Frogel, Submitted to *Icarus*

"Photometry of Phoebe (S9)," by S. Kruse, J.J. Klovett, and E.W. Dunham, Submitted to *Icarus*

"Structure of the Uranian Rings. II. Perturbations of the Ring Orbits and Widths," by R.G. French, J.L. Elliot, and S.E. Levine, *Icarus*, (in press).

"The 7 and 25 June 1985 Neptune Occultations -- Constraints on the Putative Neptune "Arc", by C.E. Covault, I.S. Glass, R.G. French, and J.L. Elliot, Submitted to *Icarus*

"What Perturbs the  $\gamma$  and  $\delta$  Rings of Uranus," by R.G. French, J.A. Kargas, and J.L. Elliot, *Science*, **231**, 480 (1986).



HIGH-RESOLUTION IMAGING OF SOLAR SYSTEM OBJECTS

Principal Investigator: Bruce A. Goldberg  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: none

#### A. Objectives:

The overall objectives are to carry out unique, high-resolution, groundbased imaging programs directed at solving specific problems in planetary astronomy; particularly those in support of deep space planetary missions. Emphasis has been on (1) the study of Io and its sodium cloud as a means for probing the inner Jovian magnetosphere on extended time scales and (2) the near nucleus regions of both active and inactive comets to determine the physical properties of their nuclei. The uniqueness is a consequence of the capabilities of the instrumentation employed, and in some cases developed specifically for these programs.

#### B. Accomplishments:

A very extensive Io sodium imaging program beginning with the first images of the cloud and culminating in comprehensive characterization of the cloud's appearance and behavior as a function of both time and Io's orbital position now forms the basis for a collaborative modeling analysis with W. H. Smyth of Atmospheric and Environmental Research and a continued observational study with emphasis on understanding how the cloud's behavior is diagnostic of spatial and temporal variations in the physical conditions of the inner Jovian magnetosphere. The sodium cloud was found to have a variety of systematic variations, a pronounced east-west orbital asymmetry, and temporal changes which could be diagnostic of time changes in both Io and its plasma environment.

New comet imaging programs initiated at the 3.6-meter Canada-France-Hawaii Telescope on Mauna Kea and AMOS/MOTIF Observatory on Haleakala draw upon both ultra-high-time-resolution and high-spatial-resolution imaging capabilities. Seven observing runs between Dec. 1984 and May 1986 were devoted (when weather permitted) to observing Halley, Giacobini-Zinner, and several other comets. Among these observations were the first images of Halley through IHW filters, and images of Giacobini-Zinner during the ICE encounter which have been directly correlated with ICE magnetic field measurements. The astronomical program at AMOS is the first ever formally supported by this facility.

#### C. Proposed Research:

Future plans are to complete the analysis and publication of observations already obtained, continue comet and possibly Io sodium observations on the 3.6-meter CFHT, and to vigorously pursue the effective utilization of the unique AMOS Observatory capabilities for planetary observing programs.

#### D. Publications:

FY 86 was a transition year to develop new data processing techniques both for the sodium and comet programs and to initiate new and extensive observing programs on two facilities which had previously provided at most minimal support to planetary programs. As a consequence, the four publications were only at the abstract level. Reference is made to B. A. Goldberg *et al.* (1984) Science 226 512-516 and cover illustration for the Io sodium program.

HIGH RESOLUTION IMAGING

Principal Investigator: Richard Goody  
 Pierce Hall  
 Cambridge, MA 02138

Co-Investigators: Costas Papaliolios  
 James Beletic

- a. Objectives To obtain diffraction-limited telescopic observations of solar system objects and to pursue a program of research into Uranus, Neptune, Pluto and the asteroids based upon the data obtained.
- b. Accomplishments
  - (i) We have developed two camera systems appropriate for this work. Most importantly, we have developed and proven the PAPA photon address camera.
  - (ii) We have developed algorithms for both phase and amplitude recovery and have proved them on theoretical and laboratory data and to a limited extent on telescopic data.
  - (iii) We constructed a laboratory simulator that has been used for development but is also available for controlled investigation of image reconstruction.
  - (iv) During 1985 we had two successful expeditions to Hawaii and Cerro Tololo and have on tape a large body of data on Pluto, Uranus, Neptune and two asteroids.
- c. Proposed Research Our proposed research is to examine in detail the 1985 data and to make a fundamental investigation of the limits to speckle imaging procedures using theoretical and controlled, laboratory images.

The first step is to reduce the Pluto data and to refine the reconstruction algorithms while doing so. The first half of this task (in collaboration with Dave Tholen of U. Hawaii) is to determine the position of Charon. We presented 35 positions on seven days to the Baltimore DPS meeting (see figure at end). After refinement of the algorithms we appear to have twice as many points at 2-4 times the accuracy.

The next step is to refine the phase algorithms. Thereafter, we shall work on the Neptune data with the aim of defining limb-darkening parameters and rotation rates at different wavelengths; we shall investigate the implications of these data for Neptune models.

The remainder of our program involves, first, reduction of the Uranus and asteroid data, comparison of the Uranus data with Voyager results, and comparison of the asteroid data with existing models. The second part of the continuing program is an investigation in the laboratory of simulated planetary images. The limits to speckle imaging can only be convincingly established under controlled, laboratory conditions when the undisturbed object is known exactly.

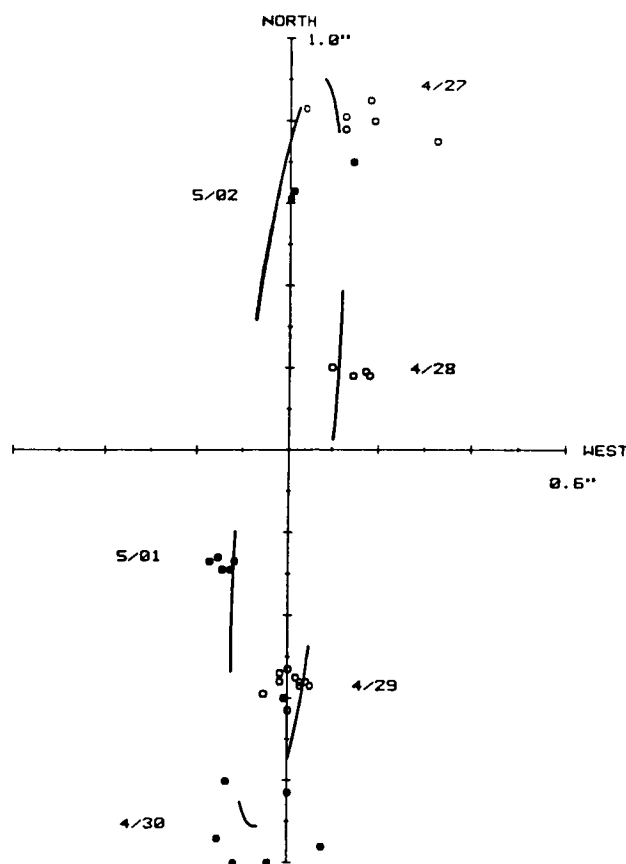
d. Publications

Nisenson, P., J. Apt, C. Papaliolios and R. Goody, 1983, "Speckle imaging for planetary research," Icarus, 53, 465-478.

Nisenson, P. and C. Papaliolios, 1983, "Effects of photon noise on speckle image reconstruction with the Knox-Thompson algorithm," Optics Comm., 47, (2).

Papaliolios, C., P. Nisenson and S. Ebstein, 1985, "Speckle imaging with the Papa detector," App. Optics, 24, 287-292.

CHARON POSITIONAL COORDINATES



## RESEARCH IN PLANETARY ASTRONOMY AND OPERATION OF THE 2.2-METER TELESCOPE

Principal Investigator: Donald N. B. Hall  
Institute for Astronomy  
Honolulu, HI 96822

Co-Investigators: Dale P. Cruikshank  
David Morrison  
William M. Sinton

### **a. Objectives of the Investigations**

The planetary astronomy program at the Institute for Astronomy is conducted in support of NASA's objective of the exploration of the solar system. Our program emphasizes three aspects of planetary science: i) extensive ground-based telescopic studies of bodies in the solar system, ii) theoretical modeling studies of telescopic data, and iii) spacecraft studies of solar system bodies through participation in the Voyager, Galileo, and other spacecraft projects. Planetary scientists at the Institute for Astronomy integrate these three lines of investigation to achieve a better understanding of solar system bodies both in preparation for spacecraft encounters with the planets, comets, and asteroids, and as a follow-up to those encounters. Through ground-based telescopic observations of the atmospheres and surfaces of solar system bodies, spacecraft experiments can be designed more effectively. Furthermore, the ground-based studies provide a longer time base and greater range of optical and infrared observations than can be conducted in a flyby or a brief orbital spacecraft encounter.

### **b. Accomplishments**

The following are highlights of the results of our investigations in 1985.

1. Detection of the turn-around in the secular change in brightness of Pluto: the planet is now beginning to brighten.
2. Detection of the spectral signature of an ammonia-bearing compound in the surface ices of Europa.
3. Detection of specific Io volcanic hotspots from infrared photometry of the mutual events of the Jovian satellites.
4. Discovery of the polarized emission from the volcanic hotspots on Io and a determination of the locations of those hotspots.
5. Refinement of the orbit of Charon from speckle observations of the Pluto-Charon system.
6. Photometry of the mutual events in the Pluto-Charon system.

7. Laboratory studies of the spectral properties of liquid nitrogen-methane mixtures with reference to the infrared spectrum of Triton.
8. Major progress in modeling asteroid lightcurves from a modern theory of photometric properties of the asteroid surfaces.
9. New results on several near-Earth asteroids.
10. Discovery of several additional olivine-rich asteroids from near-infrared spectrophotometry.
11. Acquisition of important photometric, spectroscopic, narrow-band imaging data on Comet P/Halley.
12. Acquisition of Schmidt photographs of Comet P/Halley and its tail.
13. Near-infrared photometry of the nucleus of Comet P/Halley and the conclusion that the surface reflectance resembles that of D-type asteroids
14. Acquisition of simultaneous CCD images and infrared images at 10  $\mu\text{m}$  of Comet P/Giacobini-Zinner.

#### c. Proposed Research

We propose to continue our productive program of observations and interpretations of solar system bodies, with emphasis on the Pluto-Charon mutual events currently in progress, high-resolution imagery of Uranus and Neptune (with associated theoretical model studies of their atmospheres), and a wide range of studies of asteroids, planetary satellites, and comets. The planetary satellite work will concentrate on infrared spectroscopy at resolution higher than has so far been achieved, using the new cooled-grating array spectrometer (CGAS) built at the Institute for Astronomy. In particular, we are searching the infrared spectra of the satellites of Jupiter, Saturn, and Uranus for spectral signatures of condensed volatiles in addition to the water ice known to exist there.

Asteroid investigations include spectrophotometric studies of the olivine-rich bodies and their relationship to the S-type asteroids. Further work on the C- and D-type asteroids and their relationship to the comets is also in progress using the low-resolution CVF spectrometers. The CGAS will be used in an extended search for the infrared signatures of organic molecules on the D-type asteroids and on the comets.

Additional comet research will consist of CCD imagery of the inner comae of active comets, the modeling of coma emissions using existing Monte Carlo simulations, wide-field Schmidt camera photography of bright comets, and the photometry with standard filters provided by the International Halley Watch program.

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INTERIORS OF THE GIANT PLANETS

Principal Investigator: W.B. Hubbard  
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Co-Investigators: none

(a) Objectives: This is a theoretical and observational project which seeks to constrain the interior structure of the Jovian planets by means of observational data obtained by ground-based astronomy. Recent work has been oriented toward a determination of oblateness from occultation measurements of the shape of planetary atmospheres. This provides a determination of the degree of central condensation of the planet, which is then compared with interior models and theoretical equations of state. Gathering further evidence about a Neptune arc system, which was discovered in the course of observations supported by this project, has recently become a major objective also.

(b) Accomplishments: As a serendipitous result of our attempts to measure the oblateness of Neptune, we discovered a partial Neptune ring (or arc) following an occultation observation on July 22, 1984. During 1985 we carefully reexamined older observations to determine whether Neptune arcs had been detected (but not identified) during previous occultations. A prime candidate was 1981N1, an object discovered by this project during observations of a Neptune appulse in May, 1981. This event was observed from two telescopes in the Catalina mountains near Tucson, separated by 6 km. At the time it was considered to be a small Neptune satellite about  $3 R_N$  from the planet, with a diameter of order 100 km. Following the detection of the 1984 arc, we reexamined the 1981 timings to see if the two chords had endpoints which would be consistent with a ring segment. The result of this analysis, which was published in Science in 1986, is that the position angles of the immersion and emersion points of the 1981 object are respectively very similar, and are closely consistent with the expected position angle of an equatorial ring segment. The positions of the immersion and emersion points agree much better with a ring segment than with the roughly circular cross-section of a small satellite.

Following this reanalysis, we contacted colleagues at Lowell Observatory (Bob Millis and Larry Wasserman) concerning their observations of the same 1981 Neptune event. The Lowell Observatory tracing shows no occultation at the time predicted for a ring. Thus the 1981 object, if an arc, must have had a longitudinal extent less than 600 km.

The characteristics of the two confirmed occultation observations of circum-Neptunian features supported by this grant are:

1984 arc: 15 km wide, length  $> 100$  km, 68% transparent,  $2.7 R_N$  from Neptune.

1981 arc (?): 80 km wide,  $100 \text{ km} < \text{length} < 600 \text{ km}$ , ~0% transparent, about  $3 R_N$  from Neptune.

It thus appears that Neptunian arcs may locally imitate Uranian rings, with the 1981 event resembling Uranus' epsilon ring, while the 1984 event was more similar to the thinner Uranian rings such as the alpha ring.



We carried out observations of another Neptune occultation on 20 August 1985. Observations attempted from Kitt Peak and Catalina Station near Tucson were clouded out, but excellent data at 2.2 microns were obtained from Cerro Tololo in Chile. No arcs were observed in the Chile data. A single pre-immersion event could be shown to be electronic in origin. No coincidences with companion data obtained by the Meudon group at ESO 100 km to the north were noted. During this same event, a coincidence detection of an arc was reported by observers at Mauna Kea in Hawaii, on the post-emersion side. Examination of our data at the corresponding time shows no event, although the noise level is very high because of large air mass.

Our 20 August 1985 data are of great interest, despite the absence of arc events, because they show a Neptunian central flash event, caused by global focusing by the Neptunian atmosphere. The stellar intensity briefly surged back to about 15% of the unocculted value near midoccultation. This is the first successful measurement of a Jovian planet central flash (there was an unsuccessful attempt by Voyager to observe the Jovian central flash). The data provide information about the temperature and/or absorbing properties of Neptune's atmosphere at pressures on the order of 0.2 mbar, as opposed to the usual occultation level at 0.001 mbar. They will also give a good independent determination of Neptune's oblateness.

(c) Proposed Research: We will carry out, in collaboration with the Meudon group, a complete analysis of the 20 August 1985 data, which will be pooled with the companion Meudon data sets from ESO and Mauna Kea. These data will provide a good determination of Neptune's oblateness, and should also provide information about the spectrum of waves in Neptune's atmosphere, via their effect on the immersion and emersion profiles and the central flash. We will attempt observations of another Neptune occultation on 4 May 1986. Observations of asteroid and other planetary occultations and Pluto-Charon eclipses will be made as opportunities occur.

(d) Publications:

"Statistical Mechanics of Light Elements at High Pressure. VIII. Thomas-Fermi-Dirac Theory for Binary Mixtures of H with He, C, and O." W. B. Hubbard and J. J. MacFarlane, 1985, Astrophys. J. 297, 133-144.

"Occultation Detection of a Neptunian Ringlike Arc." W. B. Hubbard, A. Brahic, B. Sicardy, L.-R. Elicer, F. Roques, and F. Vilas, 1986, Nature 319, 636-640.

"1981N1: A Neptune Arc?" W. B. Hubbard, 1986, Science 231, 1276-1278.

"JHK Photometry of Candidate Stars for Occultation by Neptune." F. Vilas and D. J. Mink, Publ. Astron. Soc. Pacific 98, 116-117.

## STUDIES OF EXTENDED PLANETARY ATMOSPHERES

Principal Investigator: Donald M. Hunten  
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Co-Investigators: Robert A. Brown

**OBJECTIVES** - This program involves telescopic observations of gases and plasmas in the Jupiter system, and related phenomena such as the recently-discovered sodium atmosphere of Mercury. It lends some support to other observational studies, principally analysis of disk spectra of Jupiter and Saturn in terms of cloud structure. The program is centered on a Cassegrain echelle spectrograph, which can also be used at a variety of lower dispersions by replacing the echelle with a suitable grating. The camera can be a CCD or an intensified CCD.

An additional task for the past year has been the construction of four occultation data systems.

**ACCOMPLISHMENTS** - Sodium absorption in Io's atmosphere was observed to distances as large as 5 Io radii during the mutual-eclipse season of the Jovian satellites. (The next opportunity for this type of work is in 1997.) This work is by N. Schneider, who realized that the absorption spectrum of Io's atmosphere could be observed when it eclipses another satellite; the phase angle is usually large enough to separate the two satellites as viewed from Earth. A curve-of-growth analysis is difficult because the velocity distribution of the sodium atoms is one of the unknowns; it is however proceeding and we expect to submit the results to *Science* before long.

During these same runs it was possible to take some data on the Mercury sodium lines discovered by Potter and Morgan. With a 4-min exposure, our data are of superior quality and give spatial resolution along the slit. There is a strong hint that the emission extends beyond the limb, but the necessary careful analysis is yet to be done.

These observations, and some described below, have made use of a CCD camera system developed by Dr. U. Fink and his group with some support from us. Although not fully operational, this camera is very sensitive and powerful, and will be of major importance for future work. Our spectrograph also is continuing to prove its power and sensitivity, as illustrated by some of the results outlined here.

Analysis of Jovian disk spectra has proceeded, as planned, from an emphasis on the  $H_2$  ortho-para ratio to analysis of methane absorptions and determination of cloud structure. This work has used the programs developed by Tomasko and his group. There are no surprises in the derived cloud properties, but the emphasis has always been on study of specific areas and any variability will not show up until the end of the analysis. One of Tomasko's students, E. Karkoschka, has begun to participate in this program with the intention of extending it to Saturn. He took some preliminary spectra during mid-1985, but the real observing campaign is planned for 1986.

Our occultation work is a continuing program, in which W. B. Hubbard of LPL is the intellectual leader. Several 2-channel photometers were constructed in 1978 for the Uranus event at which the rings were discovered (not by our teams, which did not have good skies), and a smaller, single-channel unit was built more recently. Although the photometers themselves

are still fully usable, the data-acquisition systems have major deficiencies, which become more and more evident in an ongoing program. A special task under this grant is to build three new data systems, in which the data stream, with accurate time information, is recorded on floppy disks by a portable microcomputer. With some supplementary funds from other sources, we actually plan to build four systems. Each system contains a second (single-board) computer, with its program in read-only memory, to acquire, format, and buffer the data. This package includes a high-precision clock and enough battery capacity to run the clock for 5 days. There is thus no need to be able to receive time signals in the field, a most valuable feature.

The first system has been running for several months; as soon as we are sure it is free of "bugs", we will start building the rest, for which all the parts are on hand. The software and firmware are running well enough for serious field use, but many improvements are planned. A Pluto eclipse was successfully observed on March 3/4, and the programs needed for analysis are more than half completed.

#### PLANNED INVESTIGATIONS

Cunningham's analysis of the Jovian cloud structure is expected to be completed, and Karkoschka has started to apply the same idea to Saturn. He will be making his first serious observations of specific regions of the planet during the coming apparition. Past experience suggests that analysis of a few nights of data will take a year or two.

Now that Brown has returned to STSI from his tour at MSFC, he intends to pick up his observing program. He will attempt to observe one potential sink for torus atoms and ions by looking for the signature of neutral sodium in the atmosphere of Jupiter. The plan is to lay the long slit of our echelle spectrograph on Jupiter's equator and record the Na D-lines at a resolution of about  $10^5$  with Fink's CCD. This combination of our stigmatic instrument with the detector's large dynamic range and photometric accuracy provides a unique capability for this attempted detection. The rotational doppler shift at the equatorial limb will provide sufficient displacement of the resonant scattering wavelength from the Fraunhofer D-line cores. If this work is successful, we will investigate the global distribution of jovian atmospheric sodium.

A second planned observing effort will be directed at the Io neutral oxygen cloud which Brown discovered some years ago. The object of detection is the collisionally-excited 6300 Å line, doppler displaced from the telluric airglow feature. An important conflict has arisen between more recent IUE observations that indicate oxygen uniformly spread around Io's orbit, and models that say ionization destroys O too quickly to allow the formation of an entire torus. We will seek new information about the spatial distribution of oxygen by very deep, long-slit exposures with our spectrograph--once again, an instrument uniquely suited to this task.

Construction of the remaining 3 occultation data systems will be completed, as will the upgrading of the software for acquisition and analysis of data.

PLANETARY INFRARED ASTRONOMY USING A CRYOGENIC POSTDISPERSER  
ON FOURIER TRANSFORM SPECTROMETERS

Principal Investigator: Donald E. Jennings  
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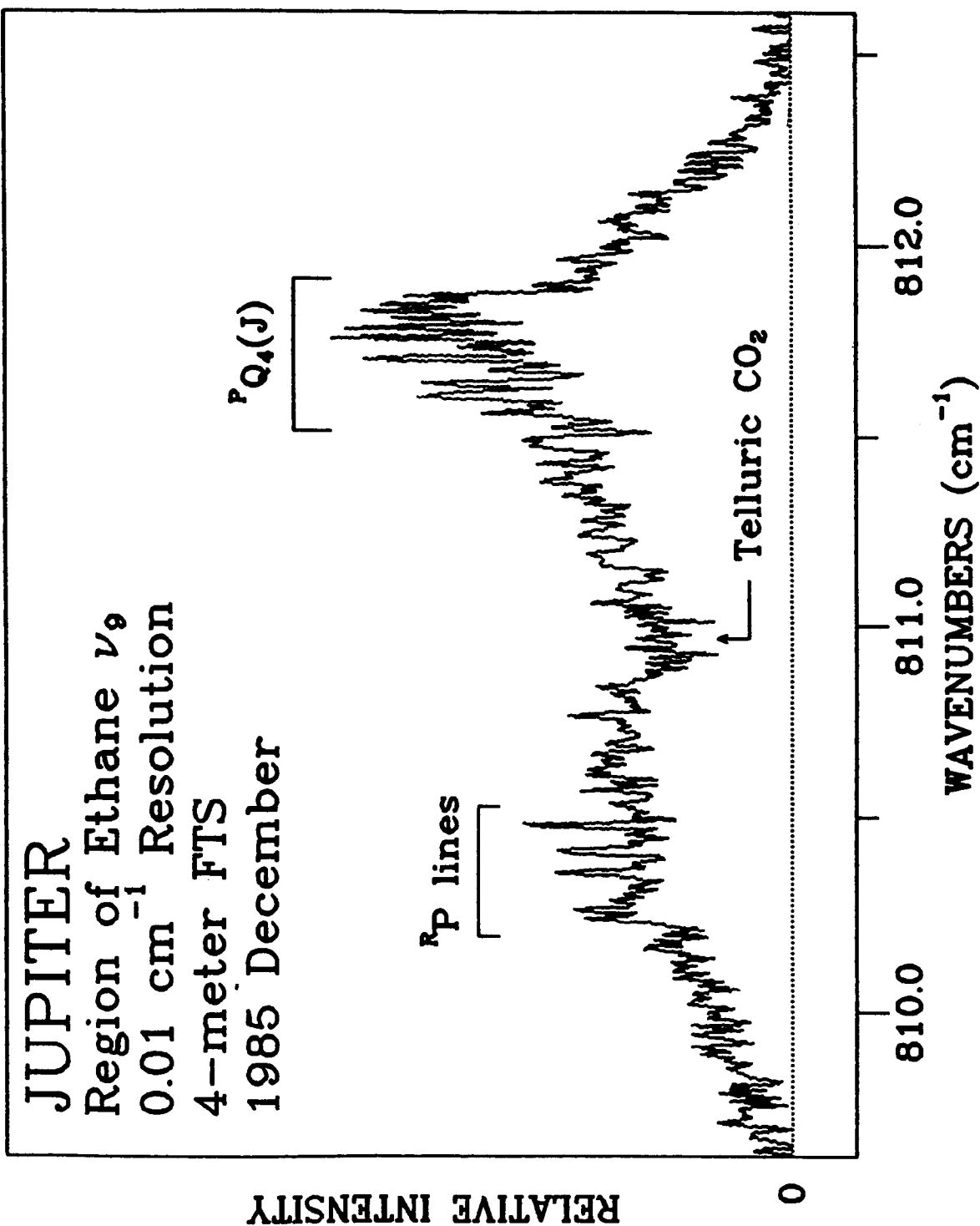
Co-Investigators: Virgil G. Kunde, Rudolf A. Hanel,  
William C. Maguire, Gerald M. Lamb,  
Gunter R. Wiedemann

**Objective:** Obtain and analyze high resolution infrared spectra of planets from ground-based observatories; develop instrumentation to improve sensitivity.

**Accomplishments:** Construction of a cryogenic postdisperser (a narrow bandpass spectral filter) for use with Fourier transform spectrometers (FTS's) at facility observatories. This instrument has improved the sensitivity of FTS observations at 8-20 microns by about an order of magnitude. Spectra of Jupiter, Saturn and Comet Halley have been obtained using the postdisperser with FTS facilities at the Kitt Peak 4-meter and McMath telescopes. Spectral resolution as high as  $0.01 \text{ cm}^{-1}$  has been achieved (see figure).

**Proposed Research:** The Kitt Peak 4-meter telescope will be used during FY87 to observe hydrocarbons in Jupiter, Saturn and Titan. Planets are observed several times a year with the McMath telescope at Kitt Peak. A large cryogenic grating spectrometer is being designed to improve both sensitivity and spectral resolution on planets.

**Publications:** This program began producing data during FY85, following completion of the instrument. A description of the postdisperser is in preparation. Spectra obtained in 1985 December and 1986 January are being analyzed in preparation for publication.



INFRARED OBSERVATIONS OF OUTER PLANET SATELLITES

Principal Investigator: T. V. Johnson  
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Co-Investigators: none

A. OBJECTIVE: This task supports IR observations of the outer planet satellites. These data provide vital information about the thermophysical properties of satellite surfaces, including internal heat sources for Io. Observations include both broad and narrow band measurements in the 2 to 20  $\mu\text{m}$  spectral range. Most observations are carried out at the IRTF facility on Mauna Kea. Types of observation and target priority are determined to make maximum use of existing data from Voyager and other missions, support on-going and planned missions such as Galileo, and to develop techniques and data for planning new missions and instrumentation.

B. PROGRESS: The program in the last year has aimed at obtaining longitude coverage on Io to establish stability of hot spot patterns previously reported. Several runs produced the most complete data set for an apparition since we started the program in 1983; unfortunately bad weather limited coverage of key longitude ranges containing the largest known hot spot Loki. Among the preliminary results (reported at the 1985 DPS meeting) is the observation of a distinct change in 4.8  $\mu\text{m}$  emission levels from the same longitudes during the summer of 1985; little or no change was observed in simultaneous 8.7 and 10  $\mu\text{m}$  data, suggesting a small, relatively hot ( $\sim 400\text{K}+$ ) spot as the possible origin of this variation. We also collaborated with W. Sinton, J. Goguen, and R. Howell on observations of a series of mutual occultation events for further localizing emitting regions on Io; these were partially successful and the data are still being analyzed. Our earlier data were used in two published analysis papers concerning correlations of hot and dark regions and models for the occultation data at several wavelengths.

C. PROPOSED WORK: During 1986 we plan a series of 3 to 4 observing sessions. Emphasis will be on studying the suspected variability of the high temperature component(s) suggested by last year's data and on obtaining longitude coverage constraining the hot spots in the Loki region.

D. BIBLIOGRAPHY: McEwen, A.S. et al., Volcanic Hotspots on Io: Correlation with low-albedo calderas, JGR, 90, 12345-12379, 1985. McEwen, A.S. et al., Calculated Occultation Profiles of Io and the Hot Sports, GRL, 13, 201-204, 1986.

## PLANETARY SUBMILLIMETER SPECTROSCOPY

Principal Investigator: M. J. Klein  
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Co-Investigators: none

Develop a comprehensive observational strategy for the detection and measurement of molecular lines in the millimeter and submillimeter spectra of planetary atmospheres and comets. A primary objective is to develop a sound observational strategy and the associated analytical capability to begin observations from the Caltech Submm Observatory (CSO) on Mauna Kea in FY 87-88.

Observed Comet Halley from the NASA-KAO with the dual-frequency (0.8 and 1.6 mm) receiver and conducted a search for NH<sub>3</sub> with the DSN 64 m antenna at Tidbinbilla.

Uranus: Remeasured the microwave (3.5 cm) brightness temperature of Uranus to confirm that polar temperature has remained above 220K prior to Voyager encounter. Interpreted VLA data of Uranus at 1, 2, 6 and 21 cm (with I. de Pater.)

Halley: Halley Microwave and Submillimeter Observations

NH<sub>3</sub>: Set upper limit to production rate from 24 GHz Observations with DSN 64m, Tidbinbilla, Australia

H<sub>2</sub>O: Set upper limit to production rate from 1.6 mm and 0.8 mm observations from NASA, KAO (May 1986)

Venus: Set upper limit to H<sub>2</sub>O mixing ratio above clouds from 1.6 mm + 0.8 mm observations from NASA-KAO flight (March 1985).

Jupiter: Continued 13 cm patrol of synchrotron emission.

Prepare for submillimeter observations from CSO. Complete the following work re current observational program:

Uranus: Update microwave measurements of variability

Venus: Publish paper on upper limit to atmospheric water vapor determined from 1.6 mm & 0.8 mm observations from NASA KAO flight.

Jupiter: Continue 13 cm Patrol of Jupiter's synchrotron flux density. Analyze time variations and search for correlations with solar wind parameters.

1) dePater & Gulkis, "Uranus' Radio Spectrum: Accurate Brightness Temperatures from VLA Data", (submitted to Icarus 1986); 2) Manietti, Green, Six and Gulkis, "Ray Tracing a Jovian DAM Radiation from Southern & Northern Hemisphere Sources: Comparison with Voyager Observations", JGR (in press).

INFRARED SPECTROSCOPY OF JUPITER AND SATURN

Principal Investigator: Roger F. Knacke  
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Co-Investigators: none

This research is a study of the composition, structure, and dynamics of the atmospheres of Jupiter and Saturn with the technique of infrared spectroscopy. Co-workers in the project are K. S. Noll (Stony Brook), T. R. Geballe (UKIRT), and A. T. Tokunaga (Hawaii). Recent emphasis has been on observations in the 5 micron region of transparency or "window" in the atmospheres of the giant planets. A detailed study in the last two years of carbon monoxide has provided new insights into the atmospheric dynamics of Jupiter, and raised interesting questions about the Saturn atmosphere.

The origin of carbon monoxide has been a puzzle for some time, and it has become apparent that CO serves as a tracer of disequilibrium processes in the Jovian atmosphere. We obtained new high resolution ( $R \sim 10^4$ ) spectra with a Fabry-Perot spectrometer at the United Kingdom Infrared Telescope in Hawaii. From a detailed synthetic spectral analysis of the CO line profiles, we could establish that the CO is located in the troposphere of Jupiter. It must therefore be a product of convection upward from hotter (1000K) levels in the deep atmosphere, and is not a product of infall of material from above the stratosphere, an alternate, but now untenable, proposal.

We have detected six lines of CO in Saturn, - a surprising result because disequilibrium models predicted that the CO mixing ratio would be too low to be observable if upward convection is the dominant mechanism. Therefore we are left with several possibilities for the origin of the CO, none completely satisfactory at this time. There could be an external source such as infall from ring material or meteors, but this would suggest a different source in Jupiter and Saturn despite similar mixing ratios. There could be an alternate chemical source such as lightning, or the convection estimates in Saturn are wrong. We are currently exploring these interesting questions. It is particularly significant that it is now possible to do comparative studies of these giant planet atmospheres using CO as a tracer.

We propose to continue observations of CO in both planets, and to study species such as phosphine and germane which are also disequilibrium products in the upper troposphere. With longer integrations, it appears possible to get CO line shape information in Saturn. If we are successful we could locate the CO in the atmosphere and thus distinguish between an external or internal source. In Jupiter, we plan to continue study of the line shapes with observations of the limbs, belts, and zones to determine the distribution of CO, cloud properties, and to obtain further insights into the convective mechanism.



Recent Publications:

The Abundances of  $\text{CH}_4$ ,  $\text{CH}_3\text{D}$ ,  $\text{NH}_3$ , and  $\text{PH}_3$  in the Troposphere of Jupiter Derived from High Resolution  $1100\text{--}1200\text{ cm}^{-1}$  Spectra (Knacke, R.F., Kim, S.J., Ridgway, S.T., Tokunaga, A.T.), Ap. J., 262, 388 (1982).

The Abundances of Ethane and Acetylene in the Atmospheres of Jupiter and Saturn (Noll, K.S., Knacke, R.F., Tokunaga, A.T., Beck, S., Lacey, J., and Serabyn, E.), Icarus, in press.

Carbon Monoxide in Saturn (Noll, K.S., Knacke, R.F., Geballe, T.R., and Tokunaga, A.T.), Ap. J (Letters), in preparation.

OUTER PLANET STUDIES

Principal Investigator: Barry L. Lutz  
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Co-Investigators: G. Wesley Lockwood

The tasks of this grant include observational studies of the composition, structure and variability of the atmospheres of the outer planets and of Titan and the investigation of the problems associated with the fundamental calibration of these data, all of which are essential to providing the ground-truth support of the Voyager and Galileo spacecraft missions. In BY86 spectroscopic studies of comet P/Halley were added to support the International Halley Watch. A modest laboratory effort designed to provide the data needed to carry out these observational programs is also maintained.

Main accomplishments during BY86 include: (1) Completion of our spectrophotometric observations of Titan and determinations of its geometric and Bond albedos and completion of like observations of Uranus, pre-Voyager encounter; (2) Completion of our study of  $\text{CH}_3\text{D}$  in the spectrum of Uranus and a determination of the  $\text{CH}_3\text{D}/\text{CH}_4$  mixing ratio in its atmosphere, (3) Completion of the observations needed for a direct calibration of the Sun against Vega; (4) Continuation of our study of  $\text{CH}_3\text{D}$  in the spectra of Saturn and Titan; (5) High resolution observations of  $[\text{O I}]$ ,  $\text{C}_2$  and  $^{12}\text{C}^{13}\text{C}$  in the coma of P/Halley.

Major efforts proposed for BY87 include: (1) Spectrophotometric observations of Uranus to accurately determine the geometric and Bond albedos post-Voyager encounter which in concert with the observations recorded pre-Voyager encounter can establish the energy budget at the time of encounter for analysis of the spacecraft data; (2) Continuation of the analysis of our spectrophotometric observations of Neptune and a determination of its geometric and Bond albedos as part of our study of temporal variability of its atmosphere, in preparation for the 1989 Voyager encounter; (3) Completion of the recalibration of the Sun against Vega and continuation of our study of the fundamental calibration problems associated with solar analogs, needed to accurately determine planetary albedos on a common photometric scale; (4) Observations of  $\text{CH}_3\text{D}$  in the spectrum of Neptune and a continuation of our study of  $\text{CH}_3\text{D}$  in the spectra of Saturn and Titan as part of our investigation of deuterium in the outer solar system and to provide complementary observations to the Voyager project and supporting studies for the Galileo mission; (5) Analysis of our high resolution spectra of P/Halley, as part of our contribution to the International Halley Watch.

## RECENT PUBLICATIONS

### (1) Papers Published in or Submitted to Refereed Journals since 1983.

"The Albedo of Uranus" (G. W. Lockwood, B. L. Lutz, D. T. Thompson, and A. Warnock), *The Astrophysical Journal* 266, 402-414 (1983).

"Monodeuterated Methane in the Outer Solar System. I. Spectroscopic Analysis of the Bands at 1.55 and 1.95 Microns" (B. L. Lutz, C. deBergh, and J. P. Maillard), *The Astrophysical Journal* 273, 397-409 (1983).

"Titan: Discovery of Carbon Monoxide in its Atmosphere" (B. L. Lutz, C. de Bergh, and T. Owen) *Science* 220, 1374-1375 (1983).

"The Albedo of Titan" (G. W. Lockwood, B. L. Lutz, D. T. Thompson and E. S. Bus), *The Astrophysical Journal*, in press (1 April 1986).

"Deuterium in the Outer Solar System: Evidence for Two Distinct Reservoirs" (T. Owen, B. L. Lutz and C. de Bergh), *Nature*, in press (July 1986).

"Monodeuterated Methane in the Outer Solar System. II. Its Detection on Uranus at 1.6 Microns" (C. de Bergh, B. L. Lutz, T. Owen, J. Brault and J. Chauville), *The Astrophysical Journal*, submitted.

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"The Abundance of Deuterium in the Outer Solar System from Ground-Based Measurements of Monodeuterated Methane" (C. de Bergh, B. L. Lutz, and T. Owen). *Rapports Isotopiques dans le Systeme Solaire (Isotopic Ratios in the Solar System)*, C.N.E.S., Paris (1984).

"A Possible Deuterium Anomaly: Implications of the  $\text{CH}_3\text{D}/\text{CH}_4$  Mixing Ratios in the Atmospheres of Jupiter, Saturn and Uranus" (B. L. Lutz, C. de Bergh and T. Owen), *Proceedings of the Conference on Jovian Atmospheres*, GISS, New York (1986).

MODELING AND INVESTIGATIVE STUDIES OF JOVIAN LOW FREQUENCY EMISSIONS

Principal Investigator: J. D. Menietti  
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Co-Investigators: J. L. Green, N. F. Six, and S. Gulkis

**OBJECTIVES:**

The objectives of the project, NASW-4045, for the fiscal year, 1985, included software development for the production of spectrograms using new recalibrated and noise-free data supplied by Professor T. E. Carr. In addition we were to incorporate a new Jovian plasma model as well as introduce the Smith et al. [1976] magnetic field model into our comprehensive ray tracing computer code. These tasks were essential to the overall project goals which include the investigation of propagation of and source regions for Jovian decametric (DAM), hectometric (HOM), and kilometric (KOM) emissions as observed by the Voyager spacecraft.

**ACCOMPLISHMENTS OF 1985:**

In the fiscal year 1985 much progress has been made in the project, NASW-4045, "Ray Tracing of Jovian Low Frequency Radio Emissions". The Voyager data in a newly produced noise-reduced and recalibrated format has been received from Professor T. E. Carr. New color spectrograms have been developed on high resolution color terminals which display this data. The production of these new spectrograms utilizing the new-format data is quite important, because it eliminates a serious problem of noise contamination and miscalibration in the old data set. We are currently modifying our sorting software so that the new data can be sorted with respect to a number of parameters including Io phase, sub-Io longitude, frequency, time, etc. This task is also deemed necessary, as such sorting has allowed the discernment of features in the data which in the past have been hard to distinguish or were obscured.

In addition, we introduced a new Jovian plasma model (Divine and Garrett, 1983) which includes the Io torus and accounts for 7 ionic species. The new plasma model will be important in the ray tracing of hectometric (HOM) and kilometric (KOM) radiation which may be influenced by the Io torus.

We have also completed work on a paper entitled "Ray Tracing of Jovian DAM Radiation From Southern and Northern Hemisphere Sources: Comparison with Voyager Observations". This paper has been submitted to the Journal of Geophysical Research. By utilizing a scheme of sorting the Voyager data with respect to sub-Io longitudes, this paper shows what we feel is a very good agreement between Voyager Planetary Radio Astronomy (PRA) observations and ray tracing results from both southern and northern hemispheres. We compare the results for both the O-4 (Acuna and Ness, 1976) and the PIOE (Smith et al., 1976) magnetic field models. We can distinguish the classical Io-B and Io-C sources as generated from a single Io flux tube. We are also compiling a second paper which attempts to explain a number of observations in the Voyager DAM data including an absence of emission near Jovian longitude 60°, as well as a discrepancy between dayside and nightside Voyager observations.

#### PROPOSED WORK:

We propose to use the modified ray tracing code which includes the new plasma model for the ray tracing of DAM, HOM and KOM emission from sources near the foot of the Io flux tube. Comprehensive ray tracing of HOM emission has not been reported in the literature, and we hope to better understand the source of this emission. We also propose to extend our ray tracing of Jovian DAM emissions to include sources from regions near the Jovian auroral zone. We believe the Jovian auroral zone may be the source of a number of as yet unexplained PRA observations. With the new Voyager data and new spectrogram and computer sorting routines we will have a much better ability to examine observational details that have missed our attention previously. For example, we will now be able to examine the DAM data in the frequency range from about 1 to 15 MHz in detail. This frequency range was previously obscured by improper calibration of the published data (Schauble and Carr, 1983). It is this frequency range which we believe contains many of the DAM emissions with origins in the southern hemisphere of Jupiter.

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SUBMILLIMETER AND MILLIMETER OBSERVATIONS OF SOLAR SYSTEM OBJECTS

Principal Investigator: D. O. Muhleman  
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Co-Investigators: none

- (a) This grant covers some of the expenses of Muhleman's planetary program at the Caltech Owens Valley Radio Observatory and, starting in Fall of 1986, the new Caltech submillimeter/millimeter telescope in Hawaii. Some funds are used for developments at the Observatories for equipment unique to planetary observations.
- (b) During the last year the millimeter wavelength 3-element array at OVRO was used to observe Halley's comet in carbon monoxide (negative result) and to set an upper limit from continuum flux of 15 km on the size of the nucleus, assumed to be a black body. The Saturn system was observed with the array and ring brightness temperatures at a wavelength of 2.7 mm were obtained. A B-ring temperature of 30 K was compared to the results at  $\lambda = 2$  cm of about 7 K indicates the measurement of true emission from the Ring particles at mm-wavelengths. Brightness temperatures of Titan, Neptune, Uranus, Io, Europa, Ganymede, and Callisto were made, all tied to Mars. We now have accurate microwave spectra of all these objects from 3 mm to 6 cm which are very important for comparative planetology.
- (c) During the next year we will carry out a six-baseline synthesis of the Saturn system at wavelength 2.6 mm (at OVRO) with the Rings essentially fully opened. We have a similar program (in collaboration with Imka de Pater) at the VLA in wavelengths 2, 6, and 20 cm. We have completed the first of 2 experiments at OVRO in the mapping of the carbon monoxide molecule in the atmospheres of Venus and Mars. We can achieve a resolution of better than 5 arc sec with the OVRO array which should enable us to measure the relationship between CO production, destruction, and flow across the terminators of these planets. The new Caltech submillimeter telescope is scheduled to begin operation in Hawaii late in the Fall of 1986. Our first experiments will be on Titan in the HCN and CO lines, first at the lower frequency transitions near 100 GHz. Hopefully, the higher frequency transitions near 200-300 GHz will be observable sometime during the next year.
- (d) Summary bibliography

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LUNAR AND PLANETARY STUDIES

Principal Investigator: D. O. Muhleman  
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Co-Investigators: none

(a) Muhleman's group report: Theoretical and model calculations of deep planetary atmospheres and scattering in the Rings of Saturn which support microwave observation in the frequency range from 1 mm to 6 cm. (b) Observations have been made and analyzed for Uranus, Saturn, and Titan in the continuum at the VLA and some spectroscopy at OVRO. Accurate A, B, C rings brightness temperatures from Saturn are a basis of scattering theory calculations. Variations of 2 cm limb darkening with pole orientation have been modeled and are shown to originate in the deep atmosphere. (c) New observations of Saturn, Venus, and Mars are currently being taken at the VLA and OVRO. A major scattering code will be written for Saturn's Rings and for the deep atmospheres (to 100 bars) of Uranus and Saturn. They expect to measure the mass of Triton. (a) Goldreich's work on planetary rings, with collaborators Borderies and Tremaine, has focused on the confinement of narrow rings, possible unstable modes of such rings and, most recently, on the newly discovered, incomplete rings of Neptune. Papers have been published, or are in press, on all of these topics. (b) The most recent paper concerns the arc-like rings about Neptune. They argue that Neptune's arc rings are located at the corotation resonances of an, as yet, undetected satellite which moves on an inclined orbit close to the planet. They demonstrate how the satellite supplies energy to the ring particles, compensating that which is lost in inelastic collisions, thus enabling the arcs to remain confined. They speculate that the unusual topology of the Neptune ring system, which we connect to the inclined orbit of this hypothetical satellite, is a consequence of the same event which produced the bizarre orbits of its satellites, Triton and Nereid. (c) Two areas of future research are the capture of material into arcs and determining the mass and trajectory of the body that must have passed through the Neptune system during the event alluded to above. (a) Ingersoll's strategy is to model the weather and climate of planetary atmospheres. Invariably, the models contain parameters that cannot be measured directly, but can be inferred from observations. (b) Accomplishments in the past year included Jim Friedson's work on the latitudinal temperature gradient on Uranus, which has been observed by Voyager at cloud top levels and by Muhleman et al. at deeper levels. (c) Work this year focuses on modeling possible water and ammonia clouds on Uranus for comparison with radio observations. (a) Ed Danielson, supported by Westphal, and a GRA are monitoring the gas/dust emissions from Halley as a function of solar distance. (b) Several observing sessions were conducted at Palomar this year with excellent results using the PFUEI CCD. (c) We plan to continue these observations as Halley retreats from the Sun.

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INFRARED OBSERVATIONS OF PLANETARY ATMOSPHERES

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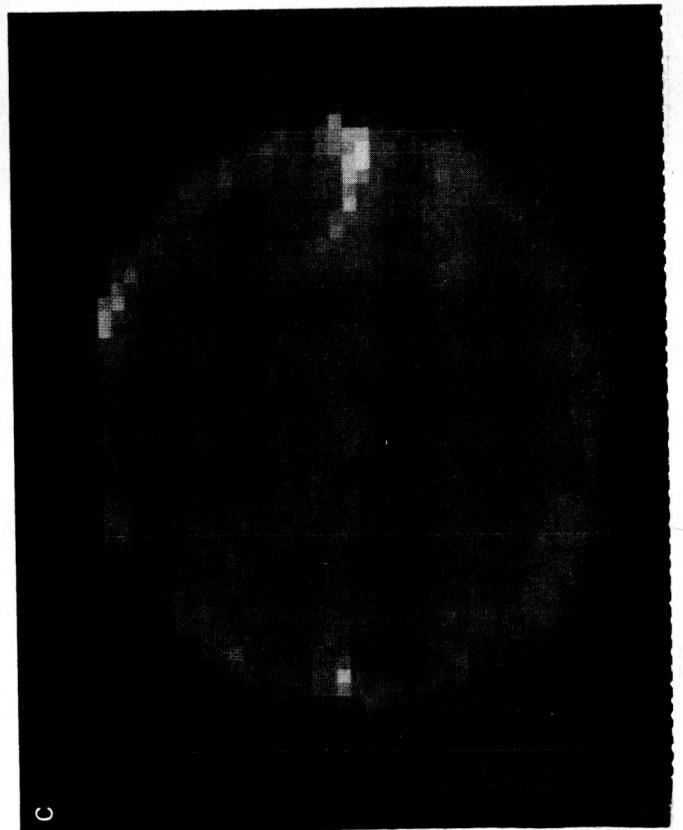
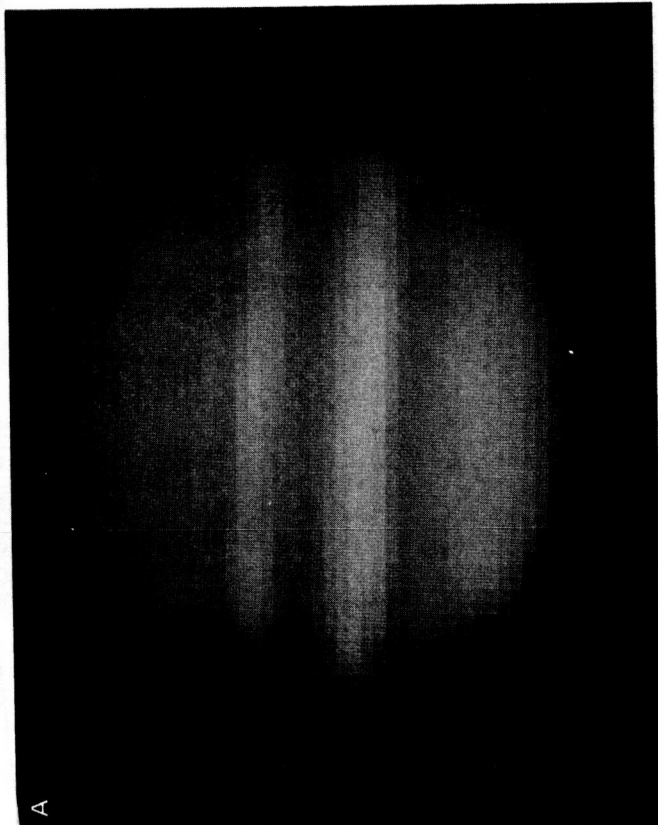
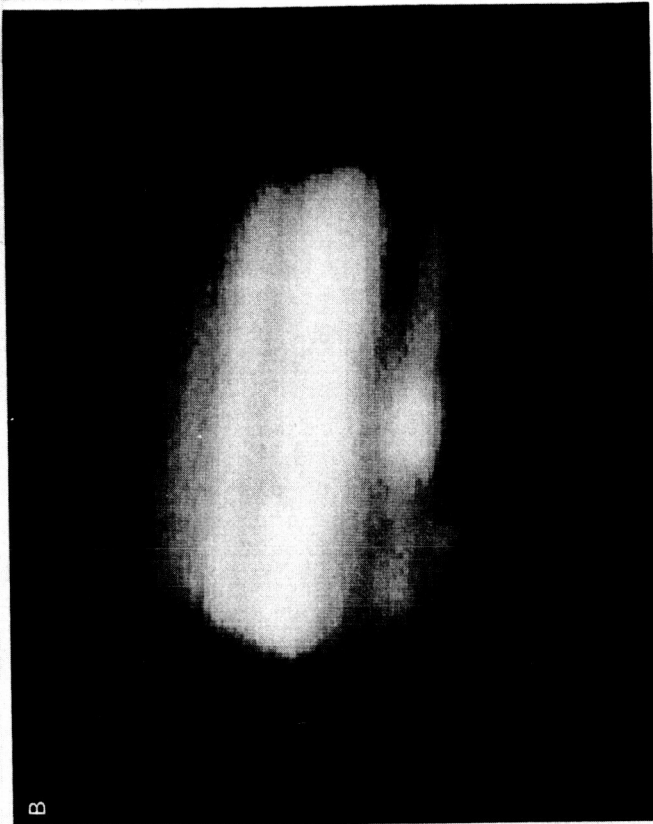
Objectives and Accomplishments: This research obtains infrared data on planetary atmospheres which provides critical information on atmospheric structure, composition, and cloud properties in support of planetary missions such as Voyager and Galileo. Mapping of Jupiter and Saturn in thermal and reflected solar radiation is a high-priority monitoring and exploratory activity. Some of these images of Jupiter are shown in the figure. Radiation at  $17.8\text{ }\mu\text{m}$  (A) probes the upper tropospheric temperature structure where spatial structure bears a strong resemblance to visible and near-infrared reflected sunlight such as at  $2.0\text{ }\mu\text{m}$  (B). At  $7.8\text{ }\mu\text{m}$  (C), stratospheric temperatures appear to have a three-banded structure, enhancements near the magnetic poles and occasional transient features such as the equatorial "filament" near the right limb. Clouds or hazes are observed high in the stratosphere looking at wavelengths such as  $2.2\text{ }\mu\text{m}$  (D), where gaseous opacity is very strong. Other maps examine cloud properties from thermal radiation not strongly influenced by gaseous opacity and the distribution of condensable gases, such as ammonia. Millimeter and submillimeter filtered radiometric observations were made of Jupiter, Uranus and Neptune via collaborative work. Radiometric observations of Uranus and Neptune at 21 and  $32\text{ }\mu\text{m}$  were acquired and analyzed as well as grating array spectra in the ranges of  $8\text{--}14\text{ }\mu\text{m}$ ,  $16\text{--}23\text{ }\mu\text{m}$ , and  $18\text{--}32\text{ }\mu\text{m}$ . These showed evidence for  $\text{C}_2\text{H}_2$  in the stratosphere of Uranus and  $\text{C}_2\text{H}_4$  in the stratosphere of Neptune.

Proposed Research: Thermal and near-infrared mapping of Jupiter and Saturn will continue, with emphasis on exploration of phenomena already observed, time scales associated with various features, and the retrieval of quantitative detail from the images requiring trustworthy absolute calibration and geometric processing. Submillimeter observations of Titan will be attempted. The absolute calibration of Uranus and Neptune will be verified in the  $8\text{--}14\text{-}\mu\text{m}$  region. Higher-resolution observations will be planned at several wavelength ranges, from  $5\text{ }\mu\text{m}$  to the millimeter.

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SPECTROSCOPIC OBSERVATIONS OF THE PLANETS

Principal Investigator: Tobias Owen  
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Co-Investigators: none

Objectives: The overall objective of this research is to obtain new information about the structure and composition of planetary and satellite atmospheres. Studies of comets are included when favorable opportunities permit. The underlying goal is to gain new insights into the processes responsible for the origin and evolution of atmospheres and the origin and cosmic distribution of life. The basic technique used in this work is spectroscopy - over the broadest possible range of wavelengths.

Accomplishments: The most significant accomplishment during the past year was the completion of the first phase of a program to determine D/H in the atmospheres of all of the major planets and Titan. In collaboration with Drs. Barry Lutz (Lowell Observatory) and Catherine de Bergh (Observatoire de Meudon), we have found that D/H on Titan and Uranus is significantly higher than on Jupiter and Saturn. Titan has the highest value, consistent with the possibility for hydrogen escape. These measurements were all made in terms of  $\text{CH}_3\text{D}/\text{CH}_4$ . They suggest that at least two reservoirs for deuterium exist in the outer solar system - a large one in hydrogen and a much smaller one in hydrogen-containing compounds that have not isotopically equilibrated with the hydrogen. This result also demonstrates that a large fraction of the carbon in the outer solar nebula was in the form of methane and it supports the nucleation model for the formation of the outer planets.

Other studies included an investigation of the phosphine abundance over the Great Red Spot (GRS) of Jupiter, pre-Voyager determination of the amount of acetylene on Uranus, and the carbon isotope ratio in Halley's Comet. UV spectra of the GRS obtained with the IUE show no evidence of the enhancement of phosphine that would be expected if the red color of this object is caused by  $\text{P}_4$  (with R. Wagener and J. Caldwell).

Proposed Research: Observing time has been requested on the Canada-France-Hawaii Telescope and its associated FTS to record the spectrum of Neptune in the region where  $\text{CH}_3\text{D}/\text{CH}_4$  can be determined. This same observing run would be used to test the feasibility of measuring D/H on Venus. Time has also been requested on the IRTF to obtain spectra of the GRS at 5 microns with higher signal to noise and higher resolution than the Voyager data. These observations will permit improved tests of various hypotheses for the "red" chromosphere(s) and will also help define the structure of the lower atmosphere inside this disturbance. Analysis of the (0,0) CN band in spectra Halley's Comet will be carried out to

determine  $^{12}\text{C}/^{13}\text{C}$  (with Drs. D. Cruikshank, B. Lutz, and M. Buie). A paper on D/H in Titan's atmosphere will be completed and submitted for publication.

Publications:

- "The Atmospheres of Icy Bodies," in Ice in the Solar System, ed. J. Klinger (Proceedings of a NATO Conference - D. Reidel, 1985).
- "The Abundance of Deuterium in the Outer Solar System from Ground-Based Measurements of Monodeuterated Methane" (with C. de Bergh and B. L. Lutz), in Isotopic Ratios in the Solar System, ed. D. Gautier (Proceedings of a CNES Conference, Cepadnes, Toulouse 1985) pp. 195-200.
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- "The Earth Among the Planets: The Origin and Evolution of Planetary Atmospheres" (General Level Review), Science Year 1985, ed. R. Such (World Book, Inc., Chicago).
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- "Constraints on the  $\text{NH}_3$  and  $\text{PH}_3$  Distributions in the Great Red Spot" (with R. Wagener and J. Caldwell), Icarus (in press).
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GROUND-BASED OBSERVATIONS OF THE JUPITER PLASMA TORUS

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Co-Investigators: Fred L. Roesler

Objectives.

The main objective in our program of Jupiter plasma torus studies is to obtain accurate data over a long time base in order to identify the persistent and transient mechanisms in the torus. It is important to obtain simultaneous measurements of ion temperatures and spatial distributions, as we have attempted previously, in order to understand how the ion distributions are related to the composition and physical parameters of the torus. By observing the torus over extended periods of time, we would increase the chance of studying transient phenomena and establishing time constants for changes in physical conditions in the torus. Such observations are important to a better understanding of the Jovian magnetosphere.

Accomplishments.

The intensity variation of [SIII] 9531 Å emission from the hot plasma torus of Jupiter was measured at Kitt Peak National Observatory during April 1982 using a scanning Fabry-Perot spectrometer. During the observational period, which covered 43 rotations of Jupiter, the [SIII] intensities showed a periodic variation consistent with a zone of enhanced emission approximately 90° in longitude, rotating with a period of 10.2 hours, or 2.8% longer than Jupiter's rotational period.

These results received considerable attention in the planetary physics community. In particular, Dessler developed a theoretical model to account for Jovian magnetospheric phenomena that differ in repetition period by 3%. In his model, periodic modulation of magnetospheric phenomena is controlled in part by the spin period of magnetic features below the surface of the planet. The differing observed periods are then due to differential rotation of the subsurface magnetic features at different latitudes. A consequence that follows from this concept of differential rotation of the internal planetary magnetic field is that not all the apparent subcorotational plasma flow in the torus is caused by plasma mass loading, as described by Hill and his associates. As a result, the mass loading required to produce the residual subcorotational flow is less than previously estimated.

Proposed Research.

We will continue the analysis of data obtained at Kitt Peak in 1982 and 1984. This data contains valuable information on the velocity distributions and densities of  $S^+$  and  $S^{++}$  ions in the torus.

We plan to continue ground-based observations of the Jupiter-torus system over the next few years in an effort to clarify our understanding of this dynamical system.

We also hope to participate in a Jupiter Watch program, which has recently been proposed informally. There have been some discussions about organizing a workshop to coordinate and encourage terrestrial observations of Jupiter, in support of the Galileo mission. We are strongly in favor of such a program which would play an important role in the study of the Jovian system.

#### Publications.

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R. Oliverson, F. Scherb, and F. L. Roesler, "The Io Plasma Torus: Its Structure and Sulfur Emission Spectra", in preparation.

A CONTINUED PROGRAM OF PLANETARY STUDY  
AT THE UNIVERSITY OF TEXAS MCDONALD OBSERVATORY

Principal Investigator: Harlan J. Smith  
 Department of Astronomy  
 The University of Texas  
 Austin, TX 78712-1083

Co-Investigators: Edwin S. Barker, William D. Cochran,  
 Laurence M. Trafton

**a. Objectives.** Our primary research goal is to further the understanding of the origin, composition, structure and evolution of our solar system in order to provide support for current NASA planetary exploration missions and to guide planning for future missions. Our large and diverse research program concentrates on both ground-based observations and theoretical investigations of the atmospheric composition, physical characteristics, and changes of the planets and satellites, as well as the physical and chemical characteristics of the comets and asteroids.

**b. Accomplishments.** During the 1985 grant year, we made the following major achievements in our program. We detected the beginning of eclipses of the Pluto-Charon system. We detected the onset of coma formation of P/Halley at 5.4 au, and had evidence of sublimation at 4.8 au when CN emission was detected. Extensive spatial maps of the gas in the comae of comets Halley and Giacobini-Zinner were obtained in fall 1985. Halley was time variable, and Giacobini-Zinner was depleted in  $C_2$  and  $C_3$  relative to CN. Comet Kopff was shown to have a pre-perihelion brightness maximum of its gas, consistent with mantle development if the comet is a high obliquity object. New Haser model scale lengths for CN,  $C_3$ , and  $C_2$  were determined using results from the Faint Comet Survey. Spectra of 12 asteroids in unusual orbits showed no evidence of any comet-like emission features. In particular, 3200 Phaethon (1983 TB) has no gas or dust coma, in spite of the similarity of its orbit with the Geminid meteor stream. We analyzed data on Saturn's  $H_2$  and  $CH_4$  bands for the recent southern summer using a Tomasko-Doose type of haze distribution. This haze model fits the data moderately well, giving a  $CH_4$  mixing ratio of  $(4.2 \pm 0.4) \times 10^{-3}$ , and  $\tilde{\omega} = 0.995 \pm 0.003$ . Simple functions have been found to approximate the collision-induced rotation-translation thermal opacity of  $H_2$ . We successfully observed the Aug. 27 eclipse of J II by Io. Io's atmosphere appears to be optically thick in the Na D lines. This enables us to set lower limits on the Na density and on the atmospheric bulk. Preliminary observations of Jupiter's  $2.1 \mu m$  spectrum, using the new multichannel infrared spectrometer, revealed spatial variations in the fundamental pressure-induced  $H_2$  feature. The high precision radial velocity spectrometer was given its first tests at the telescope, and a new cassegrain spectrograph with a CCD detector was installed on the 2.7m telescope.

**c. Proposed Research.** We will make a strong effort to pursue the following research goals, weather, telescope scheduling, equipment, and personnel commitments permitting. Spatially resolved observations of the coma of P/Halley will be obtained as it recedes from the sun. These data will serve as constraints to non-equilibrium chemical models. We will participate in the following International Halley Watch networks: Near Nucleus Studies, Spectroscopy, and Photometry. We will continue photometric observations of the Pluto/Charon eclipses, and will obtain spectra of selected  $CH_4$  bands between  $0.75$  and  $2.4 \mu m$  during and near eclipse. We will observe Triton's

2.16 $\mu$ m feature at high spectral resolution to see if it really arises from liquid N<sub>2</sub>. We will take advantage of the near pole-on orientation of Uranus to obtain very high spectral resolution observations of the H<sub>2</sub> quadrupole lines to measure their pressure narrowed and pressure shifted profiles. We will also obtain spectra of solar lines reflected from Uranus for studies of Raman scattering in the atmosphere. We plan to continue study of Triton's and Pluto's bulk atmosphere and energy balance, and to do further analysis of Raman scattering in the atmospheres of the outer planets and Titan.

#### **d. Publications during past year.**

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"C<sub>2</sub> Photolytic Processes in Cometary Comae" A. L. Cochran, Ap. J. **289**, 388, 1985.

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GROUND-BASED STUDIES OF JUPITER, URANUS, AND NEPTUNE IN SUPPORT  
OF THE GALILEO AND VOYAGER MISSIONS

Principal Investigator: Wm. Hayden Smith  
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Co-Investigators: none

Objective

Resolved line profiles for  $H_2$ , obtainable due to the pole-on aspect of Uranus, will determine the scattering and vertical structure of Uranus' atmosphere.

Accomplishments

We have obtained profiles for Uranus at a spectral resolution exceeding 450,000 for four quadrupole lines of  $H_2$ . A preliminary reduction of the line profile for the  $S_3(0)$  transition is shown in Figure 1. The profiles are all asymmetric, with a sharp blue wing, a broad red wing and a flat core, as expected from model computations (Cochran and Smith, 1983). The new observations will constrain models for the vertical structure of Uranus' atmosphere in the interpretation of Voyager data for the atmosphere of Uranus.

Objective

Determine reliable D/H Ratios for the outer planets to constrain predictions for planetary formation modes.

Accomplishments

Excellent data for the determination of the HD abundance for Uranus has been obtained during the past year for the  $R_5(0)$  and  $R_5(1)$  transitions. An HD profile is shown in Figure 2. Preliminary analysis yields a value for the D/H ratio similar to that for Jupiter ( $10 \pm 3 \times 10^{-5}$ ). A paper for Jupiter observations has already been submitted for publication. D/H data for Neptune have been obtained and are being analysed in view of our new  $H_2$  observations mentioned below.

Objective

To determine atmospheric pressure and temperature for "hot spots" in Jovian atmosphere, and ascertain the horizontal distribution of  $NH_3$ .

Accomplishments

We have obtained complete spatial coverage of Jupiter in spectrally resolved  $NH_3$  lines for which we know the molecular parameters. The observations are temporally simultaneous with the JPL group's infrared mapping. The dynamic nature of Jupiter's atmosphere makes such simultaneous studies essential to constrain the Jovian atmospheric models at a specific time rather than averaging over some arbitrary time period. An example spectrum is shown in Figure 3. The selected features of  $NH_3$  are indicated. These data will also provide temporally distinct horizontal profiles for  $NH_3$  to compare with IRIS observations being studied by Conrath and co-workers. At the same time, we obtained observations with extensive spatial coverage for the  $S_4(1)$ ,  $S_4(0)$ ,  $S_3(1)$ , and  $S_3(0)$   $H_2$  quadrupole transitions. We have emphasized the same regions studied by the JPL group so that the data sets overlap temporally and spatially. These data represent a unique opportunity to assess the vertical structure of the atmosphere of Jupiter at specified times and places.

#### Objective

This year Voyager has flown past Uranus on towards Neptune. It is our continuing interest to obtain spectra for Neptune to establish a meaningful baseline atmospheric model for that planet.

#### Accomplishments

We have observed the  $S_4(1)$  and  $S_3(1)$   $H_2$  features for Neptune. A totally unexpected result has emerged. While the  $S_4(1)$  feature has the same equivalent width as for Uranus, the  $S_3(1)$  feature is about 40% smaller. This result is being incorporated in baseline models.

#### Objective

Observation of spectrally resolved line profiles for  $CH_4$  lines in Titan is diagnostic of the pressure-temperature profile and the scattering conditions in Titan's atmosphere.

#### Accomplishments

Our Titan observations this year have confirmed our previous observations of the 6819 Å  $CH_4$  feature for Titan. The profile width is consistent with the surface pressure determined via Voyager observations. The strength of the feature is apparently inconsistent with our earlier measurements for the 6197 Å  $CH_4$  feature. We have completed low temperature laboratory observations which provide accurate molecular parameters for interpreting these observations. The discrepancy in relative strengths for the features persists. A review of our outer planetary data indicates a lesser, but similar discrepancy appears for these two features in the major planets. The discrepancy may originate in the differences in line formation for stronger and weaker lines in highly scattering atmospheres, or in the characteristics of the photolytically produced aerosol in the atmospheres of the major planets and Titan.

#### Objective

To determine ortho-para ratios for  $H_2$  in the atmospheres of the outer planets and its relationship to the convective and diffusive transport of  $H_2$  from lower depths in these atmospheres.

#### Accomplishments

In 1978, I described the ortho-para ratio for  $H_2$  in the outer planets in the context of the then extant observations, concluding that the data were consistent with equilibrium  $H_2$  for all the major planets. IRIS observations of Jupiter indicate (Gierasch and co-workers) deviations from an ortho-para equilibrium in portions of the Jovian atmosphere. High spectral resolution observations at high spatial resolution for 3-0 and 4-0 transitions of  $H_2$  are being obtained to solve this question of any deviations from an ortho-para equilibrium. The asymmetry of the line profile, as seen for Uranus, is a new and powerful probe of the ortho-para ratio as a function of the depth in the observed atmosphere. In 1989, the ortho-para ratio investigations will be extended by IRIS to include Neptune. One may speculate that Neptune's highly active atmosphere may generate large ortho-para deviations. It is also likely that spatially and spectrally resolved  $H_2$  profiles will complement the anticipated Galileo observations with NIMS.

Proposed Ground-based Observations in Support of  
Voyager and Galileo

During the coming year, global pressure-temperature-abundance profiles for Jupiter will be mapped via the  $\text{NH}_3$  transitions. The 5 micron "hot spots" will be surveyed via our  $\text{NH}_3$  profiles. Observations for the  $\text{H}_2$  transitions sensitive to ortho-para ratios will provide a complementary measurement of the vertical ortho-para distribution to IRIS data. Measurements of D/H ratios in the major planets and the continuum albedo anomaly in Titan will be reaching their conclusion.

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3. The Effective Temperature of the Line Forming Region for Jupiter (with K. Baines), *Icarus*, in preparation
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6. Spatially Resolved Profiles for  $\text{H}_2$ ,  $\text{NH}_3$ , and  $\text{CH}_4$  in Jupiter; An Inhomogeneous Atmospheric Baseline Model, (with W. Cochran, W. Schempp, and K. Baines)
7. Spectral Imagery for Saturn in the  $\text{H}_2$   $\text{S}_3(1)$  Transition, *Icarus*, (with W. Schempp), to be submitted.

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1. Hydrogen Broadening of Vibrational-Rotational Transitions of Ammonia Lying Near 6450 A, (with C.E. Keffer and C.P. Conner) *J. Quant. Spectrosc. Rad. Transf.*, 33, 193 (1985)
2. Gas Phase Cryogenic Photoacoustic Detector, *Rev. Sci. Inst.* (with C.E. Keffer and C.P. Conner), in press.
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4. Pressure Broadening in Methane in the 6190 A and the 6820 A Bands at Low Temperatures, *J. Quant. Spectrosc. Rad. Transf.* (with C.E. Keffer and C.P. Conner), in press.
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RESEARCH IN PLANETARY ASTRONOMY AT PALOMAR OBSERVATORY

Principal Investigator: B. T. Soifer  
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Co-Investigators: P. Goldreich

**Objectives:**

The goals of this program are three fold:

- (i) to study the ring systems in the outer solar system
- (ii) to search for new comets and asteroids in the solar system, and
- (iii) to study the volatile surface coverings of the primitive bodies in the outer solar system via infrared spectroscopy.

**Accomplishments:****Occultation Studies of Neptune and Uranus Ring Systems:**

We have undertaken, in collaboration with Nicholson of Cornell, an extensive series of occultation observations of stars by Neptune. During 1985 two occultations were observed with the 200-inch Hale telescope, and three were observed with the IRTF. Most of these events were predicted by Nicholson and Matthews, working in collaboration with G. Gilmore of the Royal Observatory, Edinburgh, based on measurements from U.K. Schmidt plates.

The brightest of these occultations, the event of 20 August 85 (UT), was also observed on several other telescopes and showed evidence for a ring. A clear signature of a ring is seen in our IRTF data shown in Figure 1. An accurate determination of the geometry for this event allowed the determination that this "ring" event occurred within the Roche limit for Neptune.

We have continued our collaboration with Nicholson in the study of the Uranian ring system via stellar occultations observed at  $2.2\mu\text{m}$ . The main effort this year went into the observation and analysis of the occultation of 24 May 1985, which we observed with the 200-inch telescope. This was a particularly important event for ground based observations, because it was the last significant stellar occultation prior to the Voyager 2 encounter.

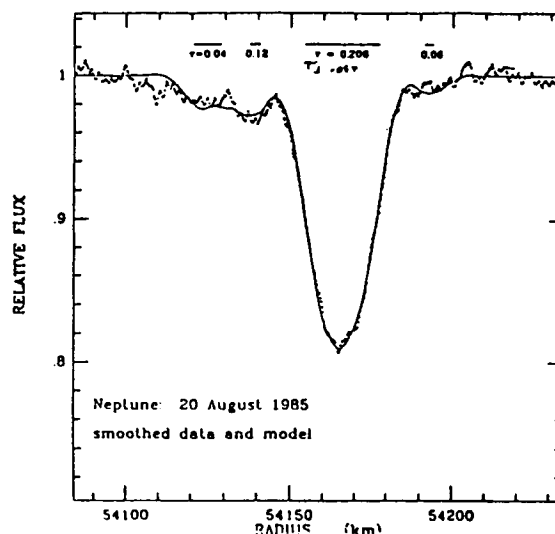
**Solar System Survey:**

The Palomar 48-inch Schmidt telescope is now fully occupied with the "Palomar Sky Survey II". Kowal has inspected the plates he obtains in this survey for comets and earth-approaching asteroids, and has trained the other Sky Survey observers in the techniques of inspection of the plates and measurement of positions. Kowal collaborated with A. Maury, the photographic specialist working on the PSSII, in identifying and measuring the locations of Comet Maury (1985k) and a fast moving asteroid.

**Cryogenic Infrared Spectrometer for the Study of Volatiles in the Outer Solar System**

During 1985 progress on the infrared spectrometer has been substantial. Tests with a single detector verified that the optics performed according to the design parameters. In addition, the stray light background in the spectrometer was reduced by over 4 orders of magnitude from the original tests. The spectrometer dewar was modified to allow the detector to operate at a temperature lower than 43K (solid nitrogen), to achieve low enough dark current to be background limited at  $2\mu\text{m}$  at a spectral resolution of  $\lambda/\Delta\lambda \sim 1000$ . The modifications have been completed, and the dewar tested. After laboratory tests are complete, the InSb array will be installed for laboratory testing, and then used on the 200 inch telescope.

**Figure 1:** The Neptune occultation event observed at  $2.2\mu\text{m}$  on 20 August 1985 using the IRTF. The solid line represents a model fit to the data that convolves Fresnel diffraction with three rings of widths and apparent optical 20 km and 0.02, 23 km and 0.2, and 10 km and 0.02 for the inner, middle and outer rings respectively.



#### **Proposed Research:**

Our current capability for observing Uranus ring occultations with both very high precision in timing and high signal to noise ratios in the events allows us to follow the structure of the rings in great detail over very long time periods. We will continue this effort by observing the occultation of 22 July 86.

The study of the Neptune ring system is in its infancy. The observations to date have demonstrated that there is a partial ring associated with this planet, but its extent, structure, and dynamics are still unknown. The question of how such a partial ring can exist is intriguing, and cannot be addressed without a substantially better understanding of its structure. We plan to observe several Neptune occultation events in the coming year. We expect to observe these using both the 5m telescope and the IRTF, including two events, on 27 July 1986 and 23 Aug 1986 that are favorable at Palomar and Mauna Kea.

The "Palomar Sky Survey II" occupies fully the 1.2m Schmidt telescope of Palomar Observatory. During the coming few years the solar system survey will consist of the careful inspection of the survey plate material to search for new comets and fast-moving asteroids. The new survey will achieve limiting magnitudes 2-3 magnitudes deeper than the previous Palomar Sky Survey, so will provide an unparalleled opportunity to find faint solar system bodies such as first time comets at great distances on a regular basis.

We fully expect to have the new infrared spectrometer on the 200-inch telescope in the coming calendar year. Initial studies with the spectrometer will involve spectra from 2 to  $4\mu\text{m}$  of the satellites of the outer planets to study their surface composition in more detail. These spectra can be used to detect minor constituents, and to obtain a better understanding of the physical and chemical characteristics of the surface layers of these objects. We shall initially emphasize spectroscopy of bodies known to have icy surfaces. Another important target will Pluto, with its methane covered surface.

#### **Publications supported by NASA Grant NGC 85-002-140**

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Many abstracts of papers given at the DPS meeting.

Many IAU circulars reporting Comet, Asteroid discoveries.

ANALYSIS OF JOVIAN DECAMETRIC DATA:  
STUDY OF RADIO EMISSION MECHANISMS

Principal Investigator: David H. Staelin  
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 Massachusetts Institute of Technology  
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Co-Investigators: none

- a) This work seeks improved understanding of the origin of Jovian decametric burst emission. The  $\sim 0.1$ -40 MHz data from the Voyager 1 and 2 Planetary Radio Astronomy experiments (PRA) are being quantitatively studied, together with related data from other sources, and are being compared to physical models.
- b) Catalogues of  $\sim 200$  decametric "arcs" and  $\sim 200$  gaps between arcs were studied,<sup>1</sup> in an effort to reconcile the data with predictions for the model wherein reflections of Io-induced currents each emit in a conical pattern and yield a distinct radio arc. Our most recent interpretations of this data suggest that these Io-produced Alfvén waves persist for at least one or two passages of Io, and that the emission cone half angles are  $\sim 40$ - $90^\circ$ , varying from arc to arc. Below 1.2 MHz we discovered that Jupiter emits radiation strongly modulated in frequency with periods of  $\sim 200$  kHz; this quasi-sinusoidal emission (MSA) can shift more than  $180^\circ$  in phase over periods of 6 seconds, although these shifts are usually much smaller. MSA is not strongly correlated with the longitudes of Io or Jupiter, and typically occurs in patches covering  $\sim 500$  kHz or more for periods of a few minutes. Furthermore, this modulation sometimes resembles a train of impulses in frequency with exponential decays toward high frequencies. Comparison of these results with our previous studies of V-shaped S-bursts<sup>2</sup> is suggestive of an emission mechanism we are exploring further. This grant ends in May 1986.
- c) We plan to complete the manuscript concerning the arc-catalogue study and our most recent interpretations, and to document our studies of the low-frequency modulated spectra activity noted above. The theoretical implications of these results are sufficiently encouraging that we plan to submit soon a new proposal focusing more intently on them.
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 2. D. H. Staelin and P. W. Rosenkranz, J. Geophys. Res., 87, 10,401-10,406 (1982).

PLANETARY FABRY-PEROT SPECTROSCOPY

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Co-Investigators: none

- a. Application of high-spectral resolution, Earth-based Fabry-Perot spectroscopy, to the study of planetary atmospheres for which current topics are outer planet HD and H<sub>2</sub> spectra (atmospheric structure, D/H ratio), Mars CO<sub>2</sub>, CO, O<sub>2</sub>, and H<sub>2</sub>O spectra (atmospheric photochemistry), Venus H<sub>2</sub>O and HDO (was Venus wet?), associated laboratory spectroscopy (especially H<sub>2</sub> 4-0 band, HDO). Monochromatic CCD imaging photometry of the Jovian nebula with images taken in rapid sequence among the diagnostic spectral lines of ionized sulfur species, providing self-supporting snapshots of the Jupiter/Io plasma conditions (spatially-resolved electron and ion densities and temperatures), covering the post-Voyager period from 1981 and leading up to the Galileo tour at the end of this decade. High-spectral resolution Fabry-Perot/CCD imaging of comets (OI, CI, and H<sub>2</sub>O<sup>+</sup> velocity maps and spatial distributions), and Io's charge exchanged neutral jet (direct probe of Io atmospheric structure).
- b. Uranus and Jupiter HD/H<sub>2</sub> spectra determine bulk D/H ratios which are significantly different from theoretical expectations with the Uranus D/H about half the Jovian value. Feasibility of Mars photochemistry study with a PEPSIOS spectrometer was demonstrated with visible band O<sub>2</sub>, H<sub>2</sub>O, and CO<sub>2</sub> spectra; and near infrared (1.57 micron) spectra of CO and CO<sub>2</sub>; and NASA/IRTF observations have been proposed in support of the Mars Observer mission objectives. Analysis of monochromatic images clearly resolve, for the first time, the azimuthal and radial structure in the Jovian nebula (ion partitioning, temperature structure, ion/neutral interactions), adding a unique and important post-Voyager perspective and providing a baseline for forthcoming Galileo experiments. Simultaneous ground based and IUE (by W. Moos) observations of Jovian nebula are under analysis. Doppler resolved image sequences (data cubes) of Io sodium neutrals clearly isolate the high velocity charge exchange jet, a sensitive ground-based probe of the tenuous neutral atmosphere of Io.
- c. Analysis of existing data and refinement of imaging data reduction techniques will continue. Spectroscopy of H<sub>2</sub> in Neptune and Uranus at Palomar 5-meter and new observations focusing on the Io atmosphere will be carried out. Comet Halley photometric and velocity resolved Fabry-Perot imaging will be analyzed in collaboration with G. Munch. NASA/IRTF spectroscopy of Mars photochemistry will be undertaken in collaboration with D. Crisp. Completion of 3 papers (outer planet HD/H<sub>2</sub>, Io atmosphere, Jovian nebula) scheduled this year.
- d. Two symposium presentations, one invited review paper, three journal articles in preparation.

VISIBLE PHASE CURVES OF URANUS AND NEPTUNE  
AND SCATTERING IN THEIR ATMOSPHERES

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As a result of my suggestion, the Voyager 1 and Voyager 2 narrow angle cameras have been imaging Uranus and Neptune (through several different filters) from distances of several AU for the past four years. The justification for this is to determine the way in which the albedoes of the two planets vary with angle from the sun (see Wenkert and Danielson, 1982). The Voyager 1 spacecraft has already reached a phase angle of  $\sim 40^\circ$  for Neptune and  $\sim 70^\circ$  for Uranus. The data being obtained is not obtainable from Earth and probably can not be obtained by Voyager 2 during the Uranus and Neptune flybys, due to scan platform problems.

I plan to use the multicolor phase curves that result from this data set in two ways. (1.) The albedo of a gaseous planet depends on the phase angle (angle from the sun through the planet to the observer), the color being observed, and the vertical distribution and nature of aerosols and clouds in the atmosphere of the planet. Since we know the colors and the phase angles I will use the phase curves to constrain models of the aerosol and cloud structures of Uranus and Neptune. (2.) A knowledge of the way albedo varies with phase angle allows one to compute the total amount of sunlight being absorbed by a planet. With knowledge of the solar flux incident on the planet and knowledge of how much infrared is being emitted by the planet (at least in the direction of the Earth and sun) one can determine a rough estimate of the internal heat source of the planet. Although Jupiter and Saturn have measured internal heat sources of magnitude comparable to their absorbed energy from the sun, preliminary results indicate that Uranus may not have an internal heat source and that Neptune if it has one that heat source is small. I intend to make better estimates of the internal heat sources for both planets, using data from a broader range of phase angles (I have only analyzed Uranus out to  $\sim 45^\circ$  and Neptune to  $\sim 25^\circ$  so far) and more recent calibrations of the cameras (to correct for any possible long term change in sensitivity of the Voyager cameras).

In practice, it will be necessary to attack the problem of the atmospheric structure before solving the internal energy source problem, for each planet. The reason is that upon solving the first problem, one derives a theoretical phase curve (which is a best fit to the observations) which can be used to fill in those phase angles (especially the high ones) which have not been observed. Bergstralh and others at JPL have been working, for several years, on the structure of the Uranian and Neptunian atmospheres. Bergstralh has a radiative transfer program, already in existence, which can be used to model the Voyager data (as well as a number of Earth based spectrophotometric data sets) and determine best fit atmospheric structures for both planets. Moreover, G. Orton (also at JPL) has a fairly detailed temperature model for both atmospheres (fitted to existing Earth based data sets in the infrared) which can be used in conjunction with my results to determine internal heat sources for Uranus and Neptune.

Reference

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### III. COMETS AND ASTEROIDS

OBSERVATIONS OF COMETS AND ASTEROIDS

Principal Investigator: Michael F. A'Hearn  
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Co-Investigators: none

Objectives:

Ultimate objective is to understand the origin and evolution of the solar system by carrying out a wide variety of observational programs on the small bodies of the solar system. The more immediate observational goal is to determine the physical and chemical nature primarily of comets and secondarily of asteroids. This requires observations at all wavelengths from ultraviolet to radio as well as theoretical modelling.

Sample of Accomplishments in 1985:

1. A'Hearn and Schnurr were one of the several teams which travelled to Mexico to observe an occultation by Ceres. The size and oblateness of this, the largest by a factor of 2 of all asteroids, were determined. The size was found to be smaller than most recent estimates but much larger than the determination from radio observations and in close agreement with the infrared radiometric determination by Lebofsky.
2. A'Hearn (and Millis at Lowell, Birch at Perth and Feldman at Hopkins) analyzed and published the observations which we had made of Comet Encke in 1984. The combination of ground-based photometry from both northern and southern hemisphere and spectrophotometry from IUE showed that the well-known asymmetry in the visual light curve of comet P/Encke was not reproduced by the vaporization of  $H_2O$  as measured by OH. Subsequent interaction with Sekanina resulted in a new model for the precession of the pole of Encke's nucleus. Although the solution for the pole led to numerical results similar to those of the previous model, it was shown that the physical mechanism was due to a major variation in the lag angle of the outgassing (i.e. in the thermal inertia of the surface) rather than a variation in the amount of ice vaporizing.
3. A'Hearn, Campins and McFadden (and Millis at Lowell) carried out extensive programs on two nearly extinct comets, Neujmin 1 and Arend-Rigaux. Both showed variations unambiguously attributable to rotation of a non-spherical nucleus with an axial ratio of 1.5 - 2.0 to 1. Mean radii of the two nuclei were found to be 10 and 5 km and both had geometric albedoes near 2%. Both were bigger and blacker than expected, just as Halley was recently found to be by Giotto. Comparison of spectral reflectivities with asteroids showed Arend-Rigaux to be similar to C-type asteroids and Neujmin 1 to be redder in the optical than any either C or D asteroids while being darker than any S asteroids.
4. Magnani and A'Hearn completed and published a theoretical analysis of fluorescence by  $CO^+$  in comets. We showed that the Swings/Greenstein effect was large enough to be used to map the acceleration of ions in cometary tails.
5. Feierberg showed that D asteroids at large distances, did not have unusually strong water of hydration thus casting doubt on their primitive nature.
6. A'Hearn provided the Ion Composition Instrument (ICI) team from ICE with relevant ground-based data on G-Z and used these results to aid their interpretation of their data.

PLANETARY RESEARCH AT THE LOWELL OBSERVATORY

Principal Investigator: William A. Baum  
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Co-Investigators: Robert L. Millis  
Barry L. Lutz  
Edward L. G. Bowell  
Tobias J. Kreidl  
David G. Schleicher

(a) Current objectives of this grant are (1) to determine photometrically the spatial distribution of grains and gases in the comae of comets by narrowband imaging with a state-of-the-art CCD system; (2) to infer sizes, shapes, irregularities, and rotation periods of quiescent (distant) cometary nuclei and other faint solar system objects by CCD imaging photometry (a new program); (3) to determine the production rates of various molecular species in comets, the scattering properties and production rate of grains, and an index of the gas-to-dust ratio by means of photoelectric photometry; (4) to determine the line-of-sight production rates of singlet oxygen in comets, the primordial  $^{12}\text{C}/^{13}\text{C}$  ratio, and the water-ice D/H ratio; (5) to investigate the structure and apparent motions of  $\text{CO}^+$  features in comet tails by very narrowband photographic f/1 imaging; (6) to derive physical and orbital parameters of the Pluto-Charon system by photometry of eclipses and transits (a new program); and (7) to maintain the archive and facilities of the Planetary Research Center.

(b) Recent accomplishments include • narrowband CCD profiles of  $\text{C}_2$  and grains in several comets (including P/Halley and P/Giacobini-Zinner), bringing the total to about 20; • rotational light curves of Comet P/Arend-Rigaux (visible and infrared) yielding the size, shape, albedo, and rotation period of the nucleus; • production rates as a function of heliocentric distance for OH, CN, and  $\text{C}_2$  in P/Giacobini-Zinner and for OH, NH, CN,  $\text{C}_3$ , and  $\text{C}_2$  in P/Halley; • detection and measurement of forbidden [O I] lines near 6300 and 5577 Å in P/Halley, permitting the production rate of oxygen from CO to be distinguished from that from  $\text{H}_2\text{O}$ ; • identification of  $^{12}\text{C}^{13}\text{C}$  lines in cometary spectra indicating a possible enrichment of  $^{13}\text{C}$  over the telluric value; • an assessment of techniques for detecting (determining the existence of) a trans-Neptunian comet belt; • substantial progress in the development of both software and hardware for pursuing the objectives of the first paragraph above; and • collaboration with many of the 24 guest investigators who spent a total of 533 days at the Center in CY1985.

(c) Research proposed for our Budget Year 1987 includes: • CCD photometry and/or photoelectric photometry of Comets P/Halley, P/Encke, P/Borrelly, P/Grigg-Skjellerup, P/Howell, P/Kopff, P/Reinmuth 2, P/Schwassmann-Wachmann 1 and 2, P/Wirtanen, and any favorable non-periodic comets which are discovered; • the systematic analysis of the

CCD profile data already in hand for C<sub>2</sub> (5130 Å) and for continuum scattering (4847 Å) by coma grains; • the addition of narrowband CCD observations for OH (3080 Å), CN (3871 Å), C<sub>3</sub> (4060 Å), CO<sup>+</sup> (4260 Å), H<sub>2</sub>O<sup>+</sup> (7025 Å), and continuum samples at 3650 Å and 6840 Å; • the systematic rereduction and analysis of narrowband photoelectric comet data acquired since 1976 in passbands like those just cited; • CCD photometry of distant comet nuclei, Trojan asteroids, and Chiron; • high-resolution echelle spectroscopy of P/Halley post-perihelion and of other selected comets; • the analysis of comet tail photographs currently being obtained; and • photoelectric and CCD monitoring of the Pluto-Charon system.

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INFRARED SPECTRAL STUDIES OF ASTEROIDS

Principal Investigator: Jeffrey F. Bell  
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Co-Investigators: none

a) **OBJECTIVES & STRATEGY:** The asteroids and meteorites are fundamental to our understanding of early solar system history since they preserve evidence of formation processes which have been destroyed by geologic activity on the planets. The principal goal of this research is to tie particular meteorite classes to specific locations in space, and specific objects which will be examined by future NASA spacecraft. The procedure followed is: 1) Employ modern astronomical instrumentation to obtain high-resolution and high-precision spectra of asteroids selected for their cosmochemical importance or role in future NASA missions; 2) compare the asteroid spectra with laboratory spectra of simulated asteroidal regoliths to determine major mineralogies and the relationship between asteroid and meteorite classification systems; 3) apply newly developed calibration techniques to determine precise mineralogies; 4) integrate the asteroidal data with the vast body of data available for various meteorite classes to reconstruct the thermal, mineralogical, and collisional histories of the asteroids and their parent bodies; 5) use the information obtained to assist in planning future asteroid missions such as Galileo and CRAF.

b) **ACCOMPLISHMENTS:** In the past two years the first comprehensive spectrophotometric survey in the near-infrared (0.8-2.5 microns) was carried out with the NASA Infrared Telescope Facility and special filters optimized for spectroscopy of solid surfaces. About 105 asteroids have been observed (in 52 photometric passbands) to date. These spectra provide a much improved database for determining the mineralogy of the various asteroid spectral classes previously defined on the basis of visible (0.3-1.0 micron) data (see Table 1). Preliminary results from analysis of these spectra include: 1) Class "A" asteroids are dominated by olivine and correspond to the rare brachinite meteorites; 2) Class "S" asteroids have highly variable olivine/pyroxene ratios inconsistent with chondritic compositions; 3) Classes "P" and "D" are apparently "ultracarbonaceous" material which extends the known range of chondrites to lower condensation temperatures; 4) the distribution of spectral types shows that the asteroids were heated by a mechanism whose intensity declined rapidly with solar distance; 5) spectra of the proposed flyby targets for CRAF (see Fig. 1) were used to evaluate the results obtainable from this mission.

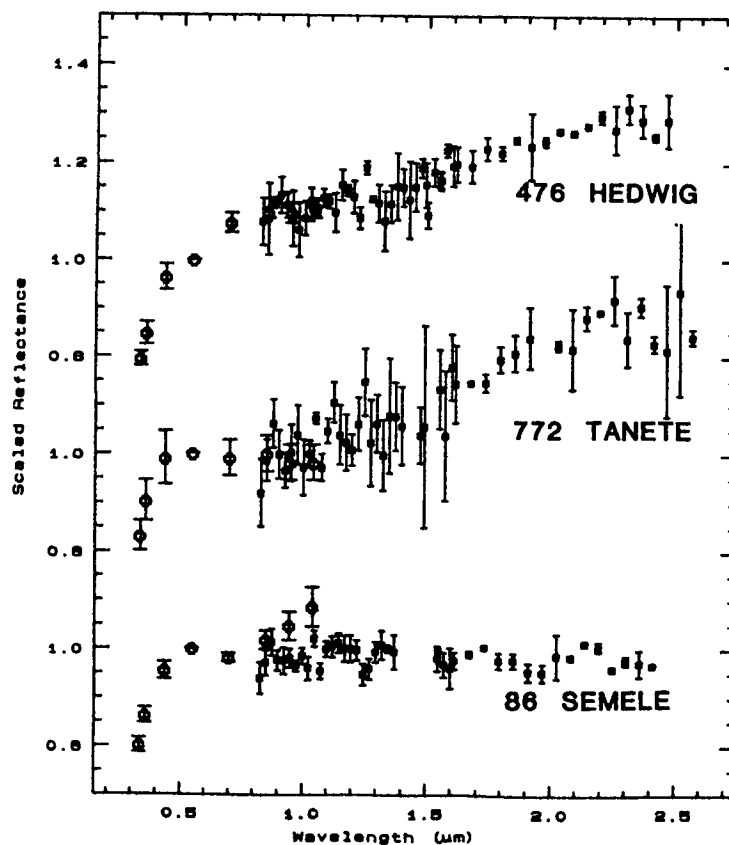
c) **PROPOSED RESEARCH:** The spectra obtained in the general survey will be published. Observations will continue to increase sampling of poorly sampled spectral classes and dynamical regions (especially Earth-crossing asteroids). Interpretation will concentrate on deriving accurate mineralogies for S-type objects, based on lab simulations of metal-rich regoliths. Assistance will be provided in the selection of flyby targets for the delayed Galileo and CRAF missions.

d) PUBLICATIONS: Bell, J.F., M.J. Gaffey, J.C. Gradie, B.R. Hawke, S.L. Gilbert, and T.B. McCord, "Surface composition and Heterogeneity of Asteroid 29 Amphitrite," Icarus, in press. Bell, J.F., "Mineralogical Evolution of Meteorite Parent Bodies", Lunar and Planetary Science XVII, p. 985. Bell, J.F., "Asteroid Dynamical Families: Mostly Mythical?" Lunar and Planetary Science XVII, p. 983.

Table 1: INTERRELATION OF ASTEROID AND METEORITE CLASSIFICATIONS:

BELL SUPERCLASS	THOLEN CLASS	INFERRED MINERALS	METEORITES
PRIMITIVE	D	CLAYS, ORGANICS	(NONE)
	P	CLAYS, ORGANICS	(NONE)
	C	CLAYS, C, ORGANICS	CARBONACEOUS CHONDRITES
METAMORPHIC	B+G+F	CARBON, MAGNETITE	METAMORPHOSED CCs
	Q	PYX, OL, Grey-NiFe	ORDINARY CHONDRITES
	V	PLG, PYX, OL	BASALTIC ACHONDRITES
IGNEOUS	R	OL, PYX	OL-RICH ACHONDRITES ?
	S	PYX, OL, Red-NiFe	LODRANITES, PALLASITES, IRONS
	A	OL	BRACHINITES
	T	??	??
	M	NiFe	IRONS
	E	Fe-free PYX	AUBRITES

Figure 1: IR Spectra of CRAF flyby candidates:



STUDIES OF ASTEROIDS AND COMETS

Principal Investigator: Edward L. G. Bowell  
Lowell Observatory  
Flagstaff, AZ 86001

Co-Investigators: Kari Lumme, Lawrence H. Wasserman,  
Tobias J. N. Kreidl, Schelte J. Bus,  
Brian A. Skiff

Principal tasks group in two areas: (1) asteroid and comet astrometry, including a photographic survey of main-belt asteroids, observations for asteroid mass determination, observation of close-Earth-approachers, and CCD astrometry of faint ( $B > 18$  mag) asteroids and comets. Scientific objectives include the discovery and follow-up of asteroids, extension of orbital arcs, recovery of asteroids and comets, and observation of close-Earth approachers at longitudes not hitherto sampled. (2) An observational and theoretical investigation of asteroid light-scattering properties, sizes, and shapes comprises observation of rotational lightcurves of small main-belt asteroids, work on magnitude statistics of a large sample of small asteroids, development of a new asteroid magnitude system, determination of asteroid shapes, surface albedo variegation, and rotational states, and development of a rather general theory for the interpretation of asteroid radiometry.

During the last year we have measured and published about 3000 accurate positions of asteroids and comets, concentrating particularly on close-Earth approachers, but also targeting asteroids in need of follow-up observations because of unusual orbital characteristics or poor observational history. In 1985, 36 of our discoveries were numbered. We made very accurate ( $\pm 0.1$  arcsec?) positional measurements of P/Halley on four nights in November and December 1985 in support of Giotto mission navigation. We continued to maintain and update our asteroid orbit files, and supplied ephemeris data for observational planning to colleagues worldwide. We made considerable progress in understanding how information on asteroid shapes, surface albedo variegation, and rotational states can be derived from lightcurve and phase curve data, publishing one paper and preparing two others. We completed the analytical formulation of a new asteroid magnitude system for the International Astronomical Union; the system was adopted at the New Delhi General Assembly by IAU Commission 20. We continued work on photographic photometry of about 10000 images of faint asteroids observed during the course of the United Kingdom Schmidt-CalTech Asteroid Survey in 1981, completing the microdensitometric scanning and all processes of software development for data handling. We have made progress on a new asteroid radiometric theory by modelling both disk-resolved and whole-disk thermal data for the Moon.

In the coming year we will pursue our astrometric projects much as before, though at a reduced rate because of budgetary constraints. Photographic astrometric objectives will be: close-Earth approachers, both newly discovered and in need of follow-up; asteroid mass determination; survey of bright main-belt asteroids; observation of numbered asteroids for ephemeris improvement;



observation of unnumbered asteroids, particularly single-apparition objects that are potentially numberable; and as-needed measurements of asteroid images from Lowell's archive plate collection. CCD astrometry will be stepped up, in particular to encompass reobservation of small UCAS asteroids, close-Earth approachers, and faint comets. We will publish our work on CCD astrometry of P/Halley, and present results at the Heidelberg ESLAB meeting in October 1986. We expect further good progress on asteroid shapes and light-scattering properties. Two or three major papers should be brought to publication and another prepared. Numerical testing of our asteroid lightcurve modelling in terms of spherical harmonics will be carried out, and results will probably be presented at the Paris Division for Planetary Sciences meeting in November 1986. Work on the asteroid magnitude system will be completed by the publication of a detailed paper. The UCAS photographic photometry task should be largely completed, with a presentation being made at the Paris DPS meeting. Work on the asteroid radiometric theory will deal with the analysis and interpretation of asteroid data, including those from IRAS. A new project will be CCD photometry of kilometer-size main-belt asteroids, for which very little is known about rotational, shape, and light-scattering properties.

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IMAGING STUDIES OF COMETS

Principal Investigator: John C. Brandt  
 Laboratory for Astronomy and Solar Physics  
 Goddard Space Flight Center  
 Greenbelt, MD 20771

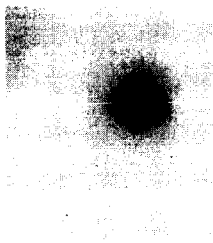
Co-Investigators: none

- a.) JOCR is located under dark skies on South Baldy mountain near Socorro, NM, and is dedicated to probing the large-scale plasma processes operating in comets, esp. the solar-wind inter-action. Toward this end, the facility conducts the most intensive wide-field ( $8^{\circ} \times 10^{\circ}$ ) imaging anywhere on earth when a bright comet is visible; the relevant instrument is a 14-inch "Comet Schmidt". Many of the recent major advances in understanding the comet/solar-wind interaction, including the rediscovery of Disconnection Events (DE's) and their interpretation under the magnetic reconnection/sector boundary model, have resulted from JOCR imagery. A 16" Newtonian/Cass. also exists on the site and is due eventually to accept a prime focus camera and a Cass. focus 2-D image-tube photon counter. Because of its complete dedication to comets, JOCR was considered, and may well prove to have been, the most important facility in the Large-Scale Phenomena Network of the IHW.
- b.) Extensive photography was conducted on comet Giacobini-Zinner in support of the flyby of the International Cometary Explorer (ICE) through the plasma tail on 9/11/85, and a dense series of plates was secured of Halley's Comet during the 7-month interval approximately centered on perihelion, i.e. 1985 November - 1986 May. The hundreds of high quality plates of Halley contain copious numbers of dramatic plasma events, including DE's, helical waves, and turning tail rays. Initial study of the plate material (full analysis will take years) lends support to the magnetic sector boundary model of DE's developed by Niedner and Brandt. The observations of Halley and G-2 were obtained at a JOCR which had been substantially upgraded in terms of physical plant and living quarters since the last FY funding cycle.
- c.) Plans include further development of the 16" Newtonian/Cassegrain instrument for observations in the post-Halley era, continued analysis of the Halley/G-2 plate material, and a sabbatical year for Dr. Elliott P. Moore (JOCR Co-Director, New Mexico Institute of Mining Technology), who is coming to NASA/GSFC to assist in the scientific analysis.
- d.) "The JOCR", J. C. Brandt, in Modern Observational Techniques for Comets, J. C. Brandt et al., ed., (NASA Doc. JPL: 81-68), p.171 (1981).
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ATLAS OF COMET HALLEY 1910 II

Principal Investigators: John C. Brandt, Bertram Donn  
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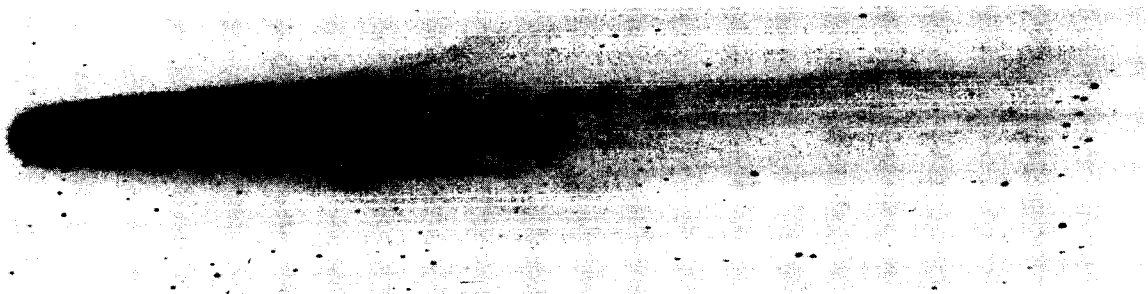
An Atlas of Comet Halley 1910 II photographs and spectra is being prepared. The major section consists of 838 photographic observations from fifteen observatories around the world. Multiple images of many photographs are reproduced to bring out detail in the near nucleus region, in the coma and in the tail. The Atlas contains a total of 1209 photographic images of the 1910 apparition. In addition there are sections showing drawings from 1835 and 1910. A short section compares 1910 drawings and photographs. The final two sections display digitally processed images from 1910 and 1910 spectra. A three part appendix contains diagrams of various data associated with the 1910 apparition, a set of tables of all 1910 images and a bibliography.



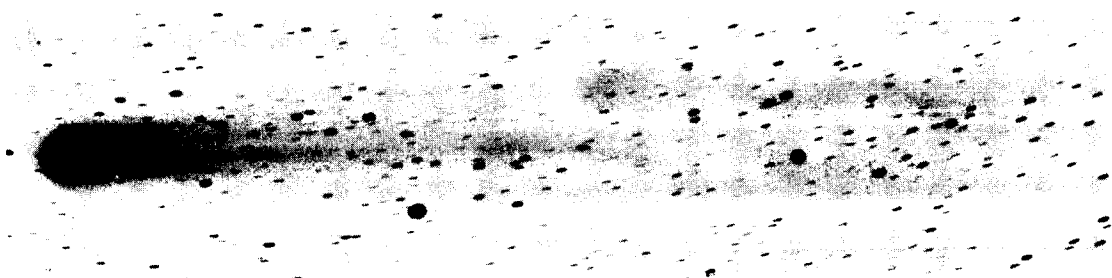
*(May 13, 1910) Lick Observatory showing details of structure near the comet nucleus.*



*(May 22, 1910) Lick Observatory showing details of structure near the comet nucleus.*



*(April 21, 1910) Harvard Observatory photograph showing complex tail structure.*



*(June 7, 1910) Córdoba Observatory, Argentina, showing another variety of complex tail structure.*

COMPOSITION OF FAINT COMETS

Principal Investigator: Larry W. Brown  
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Co-Investigators: none

Objectives: Comets are intrinsically of interest because they are believed to represent the most primitive samples of early solar system or interstellar matter. Bright spectacular comets, making their initial appearance in the inner portions of the solar system, are thought to be unevolved comets, and therefore representative of the conditions in interstellar matter. In contrast, the periodic comets, whose orbits lie primarily within that portion of the solar system occupied by the planets, are thought to be highly evolved comets, representative of the initial state modified by the environment of the inner solar system. Recent work has shown that the division may be artificial since the average physical and chemical properties of the two groups differ but little. In reality, differences in individual comets are much more pronounced. The observational data available are generally limited to the brighter and more spectacular comets or to the closest approach of faint comets. The rare occurrence of such comets leads to the use of many different telescopes and a wide variety of auxiliary equipment resulting in unknown systematic errors.

The goal of this task is to obtain sufficient systematic observations with the same telescope to determine if natural divisions exist in the physical and chemical properties of comets. The long range goal is to determine if these natural divisions (if they exist) are an indication of the age or evolution of comets.

Accomplishments: The study uses an emission line, differential imaging camera built by the Science Operations Branch. This instrument allows photometric data to be obtained over a large area of a comet in a large number of resolution elements. The detector is a 100x100 Reticon array which with interchangeable optics can give resolutions from 2" to 30" over a field of 1' to 15'. The camera through its controlling computer can simultaneously take images in on-line and continuum filters and through computer subtraction and calibration present a photometric image of the comet produced by only the emission of the molecule under study. Initial work has shown two significant problems. First the auxiliary equipment of the telescope has not allowed the unambiguous location of faint comets so that systematic observations could be made, and secondly initial data has not shown much molecular emission from the faint comets which were located. Work last year on a software and hardware display system and this year on additional guide motors on our 36-inch telescope has allowed the differential camera to act as its own finder and guide scope. Comet IRAS was observed in C2 and CO+, as well as an occultation by the comet of SAO029103. The periodic comet Giacobini-Zinner was also observed in C2. Observations of Halley are still ongoing.

Proposed Research: The comet study will continue using the differential camera in its photon-counting mode. The camera will be upgraded in the near future with a 512x512 CCD detector. Fainter comets will be investigated over a larger range of their orbits.

References: "C2 Imagery of the Inner Coma of Comet IRAS-Araki-Alcock" Brown, Oliverson, Hollis; AAS 166th meeting, Sky & Telescope, and Icarus, 63, 339, 1985.

"C2 Imagery of Comet Giacobini-Zinner" Brown, Oliverson, Hollis (preparation)

INFRARED OBSERVATIONS OF SMALL SOLAR-SYSTEM BODIES

Principal Investigator: Robert H. Brown  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California 91109

Co-Investigators: none

(a) Objectives

This new proposal describes a research program concerned with the surface properties of asteroids and icy satellites. The three major areas of investigation are: (1) A search for methane clathrate, ammonium hydroxide and carbon monoxide clathrate on icy satellites, (2) Continuation of a program begun in 1984 on separate funding to obtain 0.8- to 2.6  $\mu\text{m}$  spectrophotometry of S-type asteroids, and (3) observations of the thermal lightcurves of asteroids during stellar occultations.

The specific goals of this program are: (1) To understand the compositional properties of icy satellites in support of the Voyager 2 encounters with Uranus and Neptune, and to constrain current models of the formation of satellites in the outer solar system; (2) To obtain reflectance data on S-type asteroids in a poorly explored region of the spectrum, in order to completely define the range of mineralogy for these asteroids and determine their relationship to asteroids in related taxonomic classifications; and (3) To obtain thermal data on asteroids during stellar occultations, which when combined with visual lightcurve data and existing thermal models will yield figures and albedo distributions for these objects. The data will also provide important constraints for improvement of asteroid thermal models.

(b) Accomplishments

This is a new proposal but there are some preliminary results. Observations of Europa using the Cooled Grating Array Spectrometer have resulted in the discovery of new absorption features in the spectrum of the trailing side of Europa which have been attributed to either magnetospherically implanted sulfur compounds or recently emplaced hydrates of ammonia. More observations are planned to determine which of these two classes of compounds are responsible.

Two asteroid occultations have been observed so far, but with some negative results (the occultations paths shifted sufficiently that the groups responsible for timing the visual occultation got no data). High-quality data in the thermal infrared were obtained nevertheless; those data are useful for constraint of thermal models of asteroids and will be analyzed in that context. Work has been completed under separate funding to perfect computer code that will fit a triaxial-ellipsoid thermal model to the IR data while constrained by the visual lightcurve.

Several more observations of the infrared spectral reflectance of S-type asteroids have been obtained and the sample is getting large enough for some preliminary analysis. The observations of S-type asteroids are continuing.

**(c) Proposed Research**

This year's program consists of: (1) Spectrophotometry in the 2.15- to 2.35- $\mu$ m region at a resolution of 125 for Europa, Ganymede, Enceladus, Ariel and Titania -- satellites that have the highest probability of having any or all of the previously mentioned volatiles on their surfaces. (2) Obtaining 0.8- to 2.6- $\mu$ m spectrophotometry at 3.5 and 5% resolution for 30-40 S-type asteroids in the main belt. (3) Obtaining thermal lightcurves at narrow band 8.7, 9.8, 10.3 and 12.5  $\mu$ m and broadband N and Q (10.2 and 20.0  $\mu$ m) for 89 Julia, 230 Athamantis and 512 Brixia (about 1-3 more objects will be added to this list as Millis and Wasserman at Lowell Observatory determine which events are most suitable). For all three tasks the data will be completely reduced under this grant (PI is proposing for separate funding for detailed analysis of the data).

**(d) Publications**

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INFRARED IMAGING AND PHOTOMETRY OF COMET GIACOBINI-ZINNER

Principal Investigator: Humberto Campins  
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Co-Investigators: none

**a. Objectives**

The purpose of this project was to study the spatial distribution and physical characteristics of the dust in the coma of Comet Giacobini-Zinner (hereafter GZ). This study was carried out before the encounter with the International Cometary Explorer (ICE) in order to enhance the safety of, and the scientific return from, this spacecraft.

**b. Accomplishments**

Infrared images and photometry were obtained to determine the spatial distribution and physical characteristics (temperature, albedo, size distribution, total mass, etc.) of the grains in the coma of Comet GZ. A 10.8  $\mu\text{m}$  image of Comet GZ obtained on 1985 August 4 as part of this project represents the first groundbased thermal-infrared image of a Comet (see Fig. 1). Among the most significant results to come out of this project are: 1) An estimate of the number of grains that the ICE spacecraft must have encountered, which led the plasma wave team (see Gurnett et al. Geophys. Res. Lett. 13, 291) to conclude that they could only detect impacts on the antennae and not on the whole body of the ICE spacecraft. 2) The discovery of a population of large grains (radius  $> 100 \mu\text{m}$ ), not observed in most other comets, which formed a curved tail near the nucleus (within 80 arcsec or 34,000 km). 3) The detection of structure in the spatial distribution in the coma of the particle albedo, which has been tentatively attributed to the presence of very fluffy grains which are likely to have multiple internal scattering of incident sunlight. The albedo map of Comet GZ was obtained by combining the 10.8  $\mu\text{m}$  image shown in Figure 1 with a simultaneous image taken at 0.68  $\mu\text{m}$ , a bandpass which isolates the scattered continuum.

**c. Proposed Research**

A systematic study of the dust properties in comets using infrared imaging is proposed. Collaboration will continue with C. Telesco of NASA-MSFC for observations at thermal-infrared wavelengths, and with M. Rieke of the University of Arizona for observations at the shorter, near-infrared wavelengths. The observing runs will be coordinated in order to obtain simultaneous near and thermal-infrared images of the comets.

So far, only single maps in each of the two wavelength regimes have been obtained. In future observing runs we plan to obtain images at several of the reflected light wavelengths (i.e., 1.25, 1.6 and 2.2  $\mu\text{m}$ ), and thermal wavelengths (5, 8, 9, 10, 11, 12, 18, and 20  $\mu\text{m}$ ). This type of observation will not only yield the spatial distribution of the albedo (as in the case of Comet GZ), but also that of the grain temperature and of the silicate emission features, if present.

There are typically several comets every year within the sensitivity of the facilities to be used. There are two types of comets which are of

particular interest. The first type includes those comets which are only bright enough to be observed when they are near the sun (such as Comet Encke), and therefore, difficult or impossible to observe in the visible. In this case, most or all of the information about the dust will come from daytime infrared observations (see Campins et al. *Icarus* 51, 461). The other type includes the low activity comets where a significant portion of the infrared radiation may be coming from the nuclear surface and not just from the coma dust. Previous observations of this type of object (A'Hearn et al. *BAAS* 16, 1026) have shown that it is possible to separate the contribution from the coma from that of the nucleus. In the past, aperture photometry has been used to estimate the amount and spatial extent of the coma contribution. However, infrared imaging is a much more powerful technique in these cases.

#### d. Publications

1. Groundbased Infrared Imaging of Comet Giacobini-Zinner: The Distribution of Dust During the ICE Flyby. H. Campins, C.M. Telesco, R. Decher, D. Mozurkewich, and H.A. Thronson Jr. *Geophys. Res. Lett.* 13, 295, 1986.
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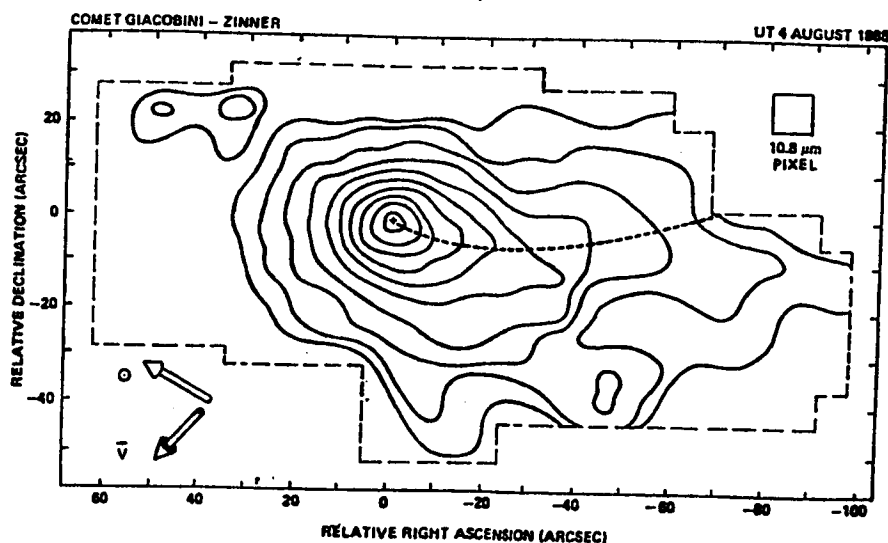


Fig. 1. A contour map of Comet Giacobini-Zinner at a wavelength of  $10.8 \mu\text{m}$ . The logarithmically spaced contour levels are: 0.20, 0.30, 0.44, 0.67, 1.00, 1.50, 2.25, 3.38, 5.06, and 7.56 Jy per pixel. The peak flux density (at cross) of 9.3 Jy was measured in the array pixel centered on the visually brightest position. The lowest contour is  $2\sigma_m$ . The side dimension of each square pixel is  $7.5$ . The region mapped is bounded by the long-dashed line. The short-dashed line is the syndyne corresponding to the locus of dust grains ejected from the nucleus at different times and for which  $\beta = 10^{-3}$ , where  $\beta$  is the ratio of radiation to gravitational forces. Vectors indicate the comet's heliocentric velocity and the direction to the Sun.



PLANETARY ASTRONOMY

Principal Investigator: Clark R. Chapman  
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Co-Investigators: D. R. Davis, R. Greenberg,  
W. K. Hartmann, S. J. Weidenschilling

Objectives. The Planetary Science Institute (PSI) is continuing a multifaceted program in Planetary Astronomy, emphasizing telescopic observations and interpretations of those data, primarily concerning comets, asteroids, and planetary satellites. The techniques we use include visible and infrared spectrophotometry, CCD imaging, precision lightcurve photometry, and broadband photometry. Our aim is to obtain data that elucidate larger issues of solar system origin and evolution, including data directed towards theoretical research we are carrying out at PSI under separate funding. The main observatories we have been using are Kitt Peak National Observatory, Univ. of Hawaii Mauna Kea Observatory, and the NASA Infrared Telescope Facility. A theme of some of our research is to understand interrelations between comets and asteroids and to search for systematic trends with distance from the sun. Another major theme is to understand the collisional processes of asteroids, which constitute the chief phenomena which stand between the present state of these bodies and their pristine character from the formative epochs of solar system history.

Accomplishments. During the past year, Clark Chapman has been studying comets during their relatively quiescent phases at large distances from the sun. This program, carried out jointly with Dale Cruikshank and other University of Hawaii staff on the UH 88-inch, has resulted in a variety of CCD images of comets in several visible and near-IR bands selected to sample the continuum, rather than emission features. The most extensive dataset was obtained for P/Halley during January 1985 (plus scattered earlier data), near the time the comet "turned on." The data have been reduced in a preliminary fashion. Other comets predicted to be relatively inactive (including Neujmin 1 and Arend-Rigaux) were more active than expected. P/Gehrels 3 was also observed.

Chapman has also been studying the spectral characteristics of Hirayama families for the purposes of understanding the compositions of proposed precursor parent-bodies. A side result of this study, reported at the 1985 DPS meeting, is that very few Hirayama families -- as identified by Williams and other researchers -- appear to show compositions different from a random selection of taxonomic types at the families' distances from the sun, using the Tholen-Gradie-Tedesco type distributions as a guide. This raises the question as to whether the families are actually "real" in a statistical or physically meaningful sense. The database for this study is a combination of the 8-color survey and Chapman's own spectrophotometric database. A preliminary report on this work is included in a paper in press in an Italian astronomical journal, and a more complete paper is in preparation.

William Hartmann has been carrying out an observational program, also in collaboration with Cruikshank, Tholen, and other colleagues using Mauna

Kea telescopes, addressing the question of the relationships between comets and asteroids. His study has focussed on "outer solar system (OSS) objects." A variety of comets have been studied, chiefly using infrared photometry, in the hopes of identifying common colorimetric characteristics which would relate them to some of the common outer asteroid compositional classes (e.g. the C's or D's). On the basis of early data on P/Halley, Hartmann and his colleagues proposed in a Nature article that Halley may be a low-albedo, reddish object. A compilation of various published albedo measurements and inferences about comet nuclei and central condensations suggests that most comets may be very dark. A paper entitled "What Does an Extinct Comet Look Like?" has been submitted to Icarus. More recently, in March 1986, Hartmann gave a talk at the Lunar and Planetary Science Conference arguing that various asteroids in loosely "comet-like" orbits tend to be more D-like in color and albedo than other asteroids.

The multi-year photometric geodesy program, being carried out jointly by Donald Davis, Stuart Weidenschilling, Clark Chapman, and Richard Greenberg -- with the assistance of David Levy and Sheila Vail -- has entered a new stage. The observing phase of the initial 5-year program will conclude with the present observing semester. A complete, penultimate reduction of all data was completed by the time of the 1985 DPS meeting, and copies were distributed to various American and overseas colleagues engaged in complementary asteroid lightcurve programs. A progress report was also presented at the DPS meeting. The preparation of the final data reduction for publication is being completed this spring and analysis of the data in terms of bulk shapes, spin parameters, etc. is underway. The dataset represents one of the largest, uniform lightcurve sets available. It has some unusual features, including the particular care paid to absolute (rather than merely relative) photometry, the wide range of non-opposition phase angles sampled, and -- the original goal of the program -- the wide range of ecliptic aspect angles sampled for the approximately dozen most completely observed asteroids.

#### Proposed Research

Chapman proposes to continue research on faint comet nuclei and on the statistics of the asteroid spectrophotometric database. He will work on P/Halley as it recedes through and past the "turn-off" point in its orbit, for comparison with the inbound data. He also expects to employ the soon-to-be-available IRAS asteroid database for extending studies of the physical properties of mainbelt asteroids (including size-distributions, albedo distributions, and taxonomic types) to smaller sizes and/or more distant parts of the main belt. A portion of Chapman's task in this program will support his Chairmanship of the Planetary Astronomy MOWG.

Hartmann proposes continued observations of comets, asteroids, and planetary satellites, with an emphasis on the middle and outer solar system in order to understand compositional gradients in the solar system and the physical characteristics of these bodies.

The photometric geodesy database will be employed to determine the body shapes, spin parameters, geophysical configurations and (depending on model parameters) the bulk densities of the observed large, rapidly

rotating asteroids, plus a few controls. Several independent approaches to determining these parameters will be employed and compared, including the traditional approaches and the Ostro-Connelly methodology (in collaboration with Ostro). When this interpretational program is partly complete, we will evaluate requirements for targeted additional observations that can help to tighten-up our results. We expect to commence the second-phase observing in the first semester of 1987.

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SPECKLE INTERFEROMETRY APPLIED TO ASTEROIDS  
AND OTHER SOLAR SYSTEM OBJECTS

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Co-Investigators: E. Keith Hege

Speckle interferometry is a high angular resolution technique that allows study of resolved asteroids. By following the changing size, shape, and orientation of minor planets, and with a few general assumptions (e.g. geometric scattering, triaxial ellipsoid figures, no albedo features), it is possible to directly measure an asteroid's true dimensions and the direction of its spin axis in one or two nights. A collection of spin axis directions may reveal the original angular momentum vector of the solar nebula, or of a few large parent bodies.

A particular subset of triaxial ellipsoid figures are equilibrium shapes, and would imply that some asteroids are thoroughly fractured. Such shapes if they exist among the asteroids would allow a determination of bulk density since there is a unique relation among spin period, size, shape, and density. The discovery of even a single rubble pile, (just as the finding of even one binary asteroid by speckle interferometric techniques) would drastically alter our notion of asteroids as small solid planets.

We have also studied the Pluto/Charon system to aid in improving the orbital elements necessary to predict the eclipse/occultation season currently in progress.

We have reduced four asteroids to their size, shape, and pole direction: 433 Eros, 532 Herculina, 511 Davida, and 2 Pallas. The overall size and shape of Eros determined with other methods was confirmed; the pole found through speckle was some 26° away from the consensus pole. The first determination of the shape and pole of Herculina was made with speckle, which also revealed a large bright area on the asteroid. Good agreement was found for Davida's pole with a variety of techniques, but speckle derived an exaggerated shape. Pallas, on two separate occasions, for two independent reductions gave conflicting results. All the discrepancies for our asteroids can be attributed to albedo variations over the asteroid, which challenges one of the basic axioms of speckle and photometry, that asteroids are uniformly coated with a regolith.

In order to circumvent the effect of these inferred spots on our power spectrum analysis, we are currently moving towards a program of image reconstruction. Measurements of these images will then provide more than just the gross size, shape, and pole; they will perhaps reveal markings, limb darkening, irregularities, etc.

Publications:

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PLANETARY SPECTROSCOPY

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Co-Investigators: none

a) The main goal of our research is infrared spectroscopic studies of the solar system in support of spacecraft investigations. Our studies include the physical behavior of comets, the atmospheres of the gaseous planets, and the solid surfaces of satellites and asteroids. In recent years we have concentrated on studies of the gaseous and solid emanations of comets using the techniques of CCD spectroscopy and imaging.

b) Last year we mounted an intensive observational effort, to observe comet Halley with our recently developed state-of-the-art CCD camera system. We spent more than a 100 nights at the telescope during the last year. This includes observations of comet P/Giacobini-Zinner. The major participants in this program were Uwe Fink, Al Schultz and Mike DiSanti. Our major emphasis was placed on spectroscopy and we were able to obtain a synoptic spectrum at least once a month. We were also able to get a large number of images of Halley for particular emission species and continuum regions. The species investigated were:  $C_3$  (4060 Å),  $CO^+$  (4505),  $C_2$  (5139),  $NH_2$  (5980),  $H_2O^+$  (6185),  $OI$  (6300 and  $CN$  (9180). In addition, we obtained a large number of images with the standard broad band photometric filters B, V, R and I. For these images we not only used the 61" University of Arizona telescope, but (when the comet became much too big for its field of view) we also used 24" focal length and 58mm focal length camera lenses. Our images showed a large number of interesting dust features such as jets, arcs, halos, as well as plasma tail features such as rays, fans and streamers. The latter features were particularly evident in our  $H_2O^+$  images. Our images have received a good distribution and have appeared in such publications such as Science (April 1986), Scientific American, Astronomy, Sky & Telescope and the Comet rendezvous asteroid flyby report. We now have a unique and excellent data set that will allow us to attack some important physical problems of comet development.

c) Now that Halley is beginning to recede from us, our emphasis will shift to analysis of our data. We will first reduce the spectra, and examine the emission features, both for the species that are expected to be present and any potential unidentified features. The broad band filter images will be used to study the development of the dust coma, and the appearance and growth of special features such as jets, arcs and halos. They can also provide photometric brightness measurements for the apparition of the comet. The narrow band filter images will yield the spatial distribution and production rates of specific emission features. All of this analysis can be carried out as a function of heliocentric distance due to the extensive time coverage of our data.

d) Summary bibliography

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PHOTOMETRY OF SMALL ASTEROIDS AND COMETARY CORES

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Co-Investigators: Wieslaw Z. Wisniewski, Ben H. Zellner

We propose to continue photometry of small asteroids in the 3-30 km diameter range and of cometary cores. This is to determine approximate lightcurves and compositional types for asteroidal bodies, and sizes for cometary nuclei.

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The first asteroid lightcurves have now been made with a new technique of CCD photometry. The apparent magnitude is fainter ( $V > 17$ ) than what can be done with the 1.52-m Catalina reflector with a photomultiplier photometer. With the CCD system of Uwe Fink, however, the lightcurve shows remarkably good repetition; finding the asteroid is, of course, no problem as the object is recognized later by its motion on the CCD.

Asteroid 1985RV has a lightcurve amplitude of about 0.4 mag and its period of rotation  $P = 4.0$  hours, on the assumption that the lightcurve has two maxima and two minima as is the case for nearly all other asteroids. The diameter is about 3 km. 1985RV is a first example of results that are being obtained on asteroids and comets with CCD in the Catalinas, Kitt Peak, and Cerro Tololo.

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CCD SCANNING FOR ASTEROIDS AND COMETS

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Co-Investigators: Robert S. McMillan

We propose to use the Spacewatch CCD-scanning system, which was built under NASW-3454, to find and follow comets and asteroids for a variety of investigations. Recovery and astrometry is to be done for selected comets and asteroids. From the large number of new asteroids discovered by the Spacewatch system, we select a few each month -- Hungaria family members for instance -- to be followed up with astrometry, as well as to be made available for other programs of spectrophotometry.

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We are using a charge-coupled device (CCD) in a scanning mode to find new asteroids and recover known asteroids and comet nuclei. Current scientific programs include recovery of asteroids and comet nuclei requested by the Minor Planet Center (MPC), discovery of new asteroids in the main belt and of unusual orbital types, and follow-up astrometry of selected new asteroids we discover. The routine "six sigma" limiting visual magnitude is 19.6 and slightly more than a square degree is scanned three times every 90 minutes of observing time during the fortnight centered on New Moon. Semiautomatic software for detection of moving objects is in routine use; angular speeds as low as 11.0 arcseconds per hour have been distinguished from the effects of the Earth's atmosphere on the field of view. A typical set of three 29-minute scans near the opposition point along the ecliptic typically nets at least 5 new main-belt asteroids down to magnitude 19.6, but we do not follow all of those. In 18 observing runs (months) we have recovered 43 asteroids, discovered and reported astrometric and photometric data on 59 new asteroids, consolidated 10 new asteroids with orbital elements, and reported photometry and positions of 22 comets.

In 1985 the Spacewatch Camera came into fruition with results on comets, asteroids, gamma-ray bursters, geosynchronous objects and brown dwarfs. Nearly 300 asteroids have been discovered to date. The astrometry turned out better than expected, better by a factor of 2 than is customary with long-focus reflectors. This is thanks to the fact that it essentially is a transit instrument when used for astrometry, with the drive off and the CCD charges transferring continuously.

The most urgent push at this time is for the installation of a 2048 x 2048 CCD instead of the present 320 x 512. This is a major development that will take two years as it is not merely the installation of another CCD, but the adaptation of all the auxiliary hardware and the software to the higher data rate. This development is essential, however, in order to detect enough comets and near-Earth asteroids.

#### Recent Publications Relevant to this work

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INFRARED PHOTOMETRY OF PERIODIC COMETS

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Co-Investigators: none

- a. Objectives: Selected comets are observed in the near-infrared (1-2.25  $\mu\text{m}$ ) and thermal infrared (3.5-20  $\mu\text{m}$ ) with the NASA Infrared Telescope Facility at Mauna Kea. The scientific objectives are to characterize the thermal emission from the dust coma, derive dust production rates, detect silicate features near 10 and 20 microns, compare thermal and scattered radiation in order to derive average albedo of the grains, and detect changes in the thermal emission which indicate changes in grain size or composition with heliocentric distance as well as differences among comets. Knowledge of the dust environment is essential to S/C design and mission planning for NASA's CRAF mission.
- b. Accomplishments: 18 comets, ranging in heliocentric distance from 1 to 5 AU have been observed with the NASA IRTF. Highlights for 1985-86 include: 1) Halley was detected 1/85 and 3/85 at R = 5 and 4.5 AU; 2) Regular Halley monitoring program was set up in collaboration with IRTF staff; 3) Nucleus of Arend-Rigaux was detected, light curve observed (0<sup>m</sup>.6 amplitude at 10 microns) and radius derived (5 km); 4) Dust coma of Giacobini-Zinner was observed at time of ICE encounter; 5) Mapping of the thermal emission spectrum simultaneously with the S/C encounters is scheduled for March 1986.

In April 1986, we will take JPL's linear array camera to the 3.9 m Anglo-Australian Telescope, where we have been allocated 6 nights to image the dust coma at 1.6-5  $\mu\text{m}$ . The array has 128 InSb detectors, allowing 1.5 x 1.5 arc min images, with 0.7 arc sec resolution. The images will be accurately calibrated, so that the dust density can be mapped across the coma and within jets.

- c. Proposed Research: In FY'87, Comet Halley will be observed until it is too faint to detect, in order to define quantitatively the level of activity vs. heliocentric distance. The body of data from the entire IRTF monitoring program will be analyzed, to obtain a self-consistent record of the evolution of the dust coma, and the infrared data will be supplied to the Int'l. Halley Watch for their archive. Other comets will be observed as appropriate; Encke and Grigg-Skjellerup reach perihelion in 1987, for example.

# RECENT PUBLICATIONS

Infrared Photometry of the Dust in Comets, M. S. Hanner, A. T. Tokunaga, G. J. Veeder and M. F. A'Hearn. Astron. J. 89, 162, 1984.

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J H K Photometry of Comet Bowell (1982 I), M. S. Hanner and G. J. Veeder. Icarus 60, 445, 1984.

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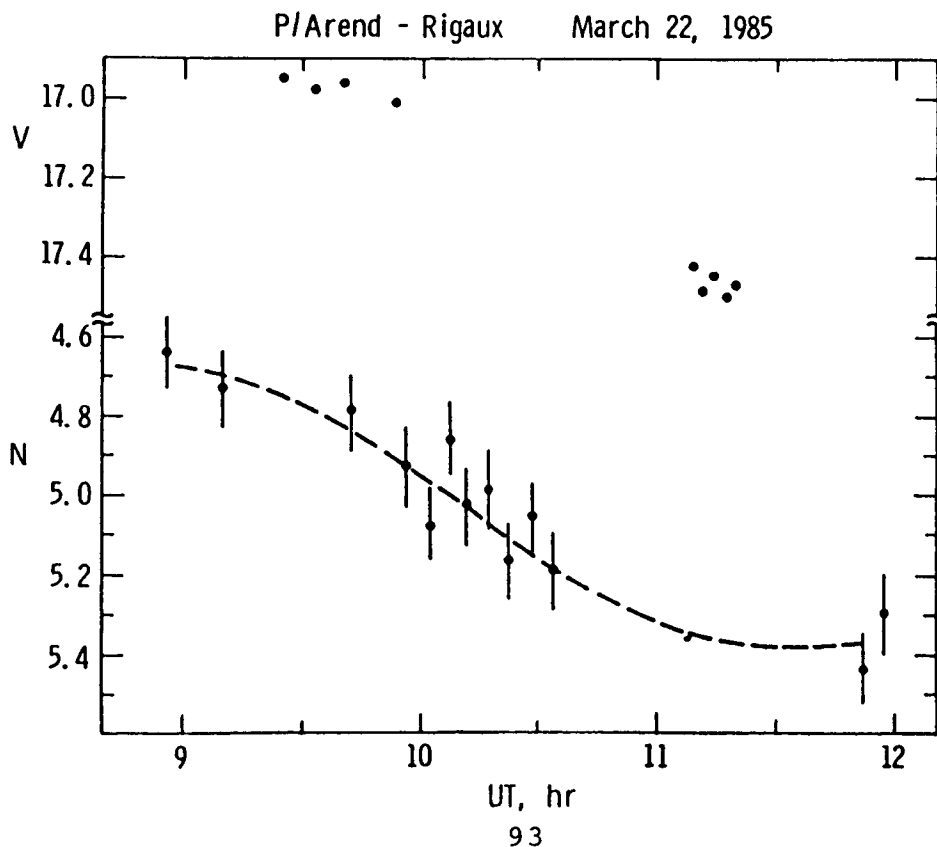


TABLE MOUNTAIN OBSERVATORY SUPPORT TO OTHER PROGRAMS

Principal Investigator: Alan W. Harris  
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 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: James W. Young

a. The objective of this task is to provide support for other programs at Table Mountain Observatory, including equipment maintenance and upgrades and limited observing support by James Young.

b. During CY 1985, over 20 asteroids were observed photometrically for period determinations and phase relation studies. These included 1036 Ganymed, the largest Mars-crossing asteroid known, and 1627 Ivar, an earth-approaching asteroid which is a potential space mission target. Research by students from Caltech, Cornell, and Harvey Mudd College was supported. David Rees of University College London was supported in obtaining Doppler images of P/Halley from TMO. Initial testing of the JPL/TMO CCD camera system was supported at TMO by imaging P/Giacobini-Zinner and P/Halley.

c. During FY 1986, observations of asteroids will continue in support of the radar observing program of Steven Ostro, occultation observations by various groups, newly discovered Earth-approaching asteroids as they are found, and phase relation studies by A. Harris and E. Bowell of Lowell Observatory. Additional observations by David Rees are being supported early in the year, and the program may be continued as suitable comets become available for observation. The student program at Harvey Mudd College is continuing, and some setup and maintenance support is provided. It is expected that a 1m telescope owned by Pomona College, but located at TMO, will become operational during FY 86. In exchange for maintenance services, JPL will have the use of one half of the observing time on that instrument. Some of that activity will be supported under this grant.

d. Recent publications include:

Ostro, S. J., Harris, A. W., Campbell, D. B., Shapiro, I. I., and Young, J. W. (1984) Radar and Photoelectric observations of asteroid 2100 Ra-Shalom. Icarus 60, 391-403.

Harris, A. W. (1986) Asteroid Lightcurve Studies. In Asteroids, Comets, Meteors, II, C.-I. Lagerkvist, B. A. Lindblad, H. Lundstedt, and H. Rickman, eds., Uppsala: Uppsala Universitet, pp35-44.

PLANET-CROSSING ASTEROID SEARCH (PCAS)

Principal Investigator: E. F. Helin  
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Co-Investigators: none

OBJECTIVES: A systematic search for planet-crossing asteroids is being conducted with the 0.46m and 1.2m Schmidt cameras at Palomar to establish improved estimates of their population and size distribution. Independent field pairs are photographed monthly; new objects are detected and followed to determine definitive orbits. When near-Earth asteroids are discovered, colleagues are informed so that physical observations may be attempted. These remote sensing techniques yield compositional information and suggest generic relationships. Populations of objects with different orbital characteristics are estimated from the observed numbers.

PROGRESS IN 1985-1986: 511 independent fields were photographed with the 0.46m Schmidt during 15 observing runs along with a limited number of 1.2m Schmidt exposures. From these fields 122 new asteroids have been reported. Special sets of field using the 1.2m Schmidt are continuing to yield numerous new faint asteroids. The combined result from both telescopes include 4 Mars-crossers, 3 Hungarias, 2 Phocaeas, a unique high inclination object (1985XB), 1 Apollo (1985PA) and Aten (3362) Khufu. Halley has been regularly monitored (astrometry and large-scale phenomena) IHW participation. Scientifically valuable photographs have been obtained from both 0.46m and 1.2m Schmidt Telescopes. Other accessible comets were observed including G-Z. Recently a new comet (1986d) was discovered. Coordination of Int. Near-Earth Asteroid Search (INAS) is progressing well with tens of discoveries from participating countries.

PROPOSED WORK: Continuation of the monthly 0.46m Schmidt survey, using pairs of short exposures for maximum sky coverage, recovery and special fields in conjunction with PSS II on the 1.2m Schmidt will comprise the planned work in 1987. Programmatically, we are incorporating with this task the "Asteroid Population" task previously covered by Planetary Geology. Additional augmentation is sought to include comprehensive measurements and data reduction of all images on current and archived plates. (Proposal to be resubmitted).

SUMMARY BIBLIOGRAPHY: Discoveries and observed positions published in 10 International Astronomical Union Circulars, 26 Minor Planet Circulars, 3 papers published, 3 abstracts published, 3 papers in press, 13 oral presentations.

RADIATIVE TRANSFER IN PLANETARY ATMOSPHERES

Principal Investigator: William M. Irvine  
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Co-Investigators: F. Peter Schloerb

a. Objectives: During the past year the emphasis of research has been on the chemical composition, gas production rate, kinematics, and variability of the molecular material in cometary comae. The goal is to improve understanding of the origin of comets, including their possible relationship to instellar clouds, and refining knowledge of the physical conditions and physical processes taking place in comets.

b. Accomplishments: The research effort has been concentrated toward comet P/Halley during the last year, although observations of other comets including Giacobini-Zinner, Hartley-Good and Thiele have been made as opportunities arise. In preparing for the apparition of P/Halley, detailed predictions for the emission in the 18 cm OH transitions were made in order to assist observers and to indicate what type of data would be particularly valuable. Likewise, since occultations by the comet of background radio sources can provide unique types of information, the tracks of P/Halley and P/Giacobini-Zinner were surveyed with the NRAO Very Large Array, background sources were mapped, and a catalogue of occulted sources published. Beginning in September, 1985, regular observations of the 18 cm OH lines have been made for P/Halley using the 43 m antenna of the NRAO in Greenbank, West Virginia. These data promise to provide the most accurate time sequence for the OH emission for any comet ever obtained at radio wavelengths. From the linewidth and shape, information is obtained on the kinetics of the gas in the cometary coma. An extensive series of observations have been undertaken with the University of Massachusetts (FCRAO) 14 m antenna to study emission from the HCN molecule in P/Halley. These data (and independent observations by colleagues in France) provide the first definitive detection of this component of the cometary ices. We have observed interesting variations in the production of HCN with time scales less than a day. Likewise, there appeared to be variations in the ratio of the hyperfine components of the  $J = 1-0$  transition; these effects are not yet understood and promise to provide a new insight into cometary activity.

c. Proposed Research: During the coming year we will concentrate on the reduction and interpretation of the observations of P/Halley and other comets observed during the past year. The H<sub>2</sub>O production rates derived from the radio OH data will be compared to information obtained from ultraviolet and optical observations to try to reconcile what appeared to be systematic differences, which may be related to time dependent effects and differing fields of view with the different instrumentation. The detailed line shapes will be correlated with evidence for cometary outbursts obtained at other wavelengths to search for asymmetries which may be indicative of jets of outgassing material in the coma. The abundance of HCN determined from our observations must be carefully evaluated, since there are a number of model dependent effects. The values obtained will be closely compared with data on CN production rates obtained from optical observations, in an effort to determine whether HCN is the primary parent molecule of the CN radical. The apparent variations in production rate and excitation of HCN will also be investigated by looking for correlations with other time dependent cometary phenomena and by calculations of the expected excitation.

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- 1985d, Lumme, K., H. Karttunen and W.M. Irvine, "Roughness of the Lunar Soil", Earth, Moon, Planets, 33, 19.
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- 1985f, Schloerb, F.P., and E. Gerard, "Models of Cometary Emission in the 18 cm OH Transitions: The Predicted Behavior of Comet Halley", Astron.J., 90, 1117.
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OPTICAL INVESTIGATION OF COMET HALLEY

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Co-Investigators: none

**Abstract:** The optical properties of comet p/Halley are being investigated. Initial research has revealed the basic characteristics of the nucleus and provided unique insights into the formation and structure of the coma and the plasma tail. Our study is among the most intensive conducted for any comet. The results from comet p/Halley may be useful in the interpretation of results from other comets.

**(a). Overview**

In this investigation we are studying the changes which occur in comet Halley as its heliocentric distance varies. Most of the observations are taken at optical wavelengths, using CCD imaging and polarimetry, Reticon spectrophotometry and wide field CCD and Schmidt imaging. The optical data are used (i). to measure the optical and geometrical properties of the nucleus (ii). to estimate the grain column density and loss rate near the nucleus, versus time (iii). to study the morphology and, especially, the time dependence of the morphology of the inner coma (jets, plumes, halos etc) in order to understand the origin of these short lived features (iv). to study the time and phase - angle dependences of the gas and grain spectra in order to learn about the optics of the optically dominant grains and changes in the dust/gas ratio in the coma (v). to follow the development of features in the plasma tail on timescales from < 1 hour to several months (with a view to finding the origin and dynamics of the various plasma structures).

**(b). Accomplishments**

We have obtained detailed physical observations of p/Halley at 10 heliocentric distances in the range  $0.9 \leq R \text{ (AU)} \leq 11$ . The bulk of the data are still being analyzed and more observations are planned. However, some early accomplishments can be summarized:

- (i). the recovery of p/Halley at  $R = 11 \text{ AU}$ .
- (ii). determination of nucleus properties from observations in the range  $6 \leq R \text{ (AU)} \leq 11$ . The brightness of the comet in this range followed the inverse square law, which, together with the stellar PSF suggests that the bare nucleus was observed. The measured nucleus properties include (a). mean product of the geometric albedo with the square of the spherical equivalent radius,  $pr^2 = 1.0 \pm 0.1 \text{ km}^2$ . (b). the nucleus is highly irregular with an equatorial axis ratio  $a/b \approx 3/1$  (c). the nucleus is red and dark, probable albedo  $p = 0.07 \pm 0.02$  (d). the nucleus is a slow rotator, with period  $T \geq 17$  hours. Our measurements of the properties of the nucleus of p/Halley are described in Meech, Jewitt and Ricker (1986). Our values appear to have been confirmed by subsequent measurements from the Vega and Giotto spacecraft.
- (iii). the photometric detection of the initial coma formation at  $R \approx 6 \text{ AU}$ .
- (iv). acquisition of about 100 high quality optical spectra around the date of phase angle minimum ( $\beta = 1$  degree in mid November 1985). These spectra are being used to study the phase dependence of the grain scattering intensity and color and to examine short term variations in the gas/dust ratio which may be associated with the rotation of the nucleus.
- (v). the first observations of a plasma tail ( $R = 1.8 \text{ AU}$  in November 1985).
- (vi). wide field image sequences at 5 heliocentric distances showing episodes of ray formation (timescale < 1 hour) and disconnection events. The Schmidt plates were taken at rates upto 5/hour,

and thus provide good resolution of rapid plasma events.

(vii). temporally and spatially resolved photometry of the inner coma at several heliocentric distances and wavelengths is being used in an attempt to see how the extreme shape of the nucleus might influence the morphology of the inner coma.

(viii). to help us interpret the photometric observations of the nucleus, we have taken and studied nuclear photometry on several other comets. We find that nuclei are typically irregular and give evidence for rotational modulation of the scattered light (Jewitt & Meech, 1985; other papers are in preparation).

(ix). to provide a standard against which to compare the optical properties of the grains in Halley, we have examined the grains in about a dozen comets at wavelengths from 0.4  $\mu\text{m}$  to 2.2  $\mu\text{m}$  (Jewitt & Meech, 1986). Our new observations permit, as a by-product, interesting comparisons of the comet grains with the interstellar grains.

#### (c). Future Research

The research planned for the next year continues and extends the above projects:

(i). Continued analysis of the wealth of observational data already in hand. We anticipate especially interesting results from the inner coma images, from the time series inner coma spectra and from the large (and growing) number of plasma tail images.

(ii). Additional observations of the comet on the outbound leg of its orbit will be obtained in order to measure pre - post perihelion asymmetries in the molecular and grain production rates.

(iii). A concerted effort will be made to re-observe the nucleus at  $R \geq 5$  AU, once the coma has substantially dissipated. Our prime goal will be to define the rotation period using the CCD photometric method we have applied successfully to other comets. The period will be compared with estimates made using less direct techniques (e.g. the curvatures of jets).

(iv). The plasma doppler shift will be measured at several locations along the length of the plasma tail. This measurement is intended to directly address the long standing problem of the nature and origin of the tailward motions seen in cometary type I tails.

#### (d). Related Publications

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Meech, K. J., Jewitt, D. C., and Ricker, G. R., (1986). Early Photometry of p/Halley: Development of the Coma, *Icarus*, in press.

Jewitt, D. C., and Meech, K. J., (1986). Wavelength Dependence of the Scattering from Cometary Grains or What Color is Comet Dust?, *Astrophysical Journal*, submitted.

COMETARY SPECTROSCOPY

Principal Investigator: Stephen Larson  
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Co-Investigators: none

This is an ongoing observational program to investigate the spectroscopic and morphological characteristics of comets over a wide range of heliocentric distances as they may suggest or constrain models of cometary formation environments and evolution. This program also contributes to the understanding of the general comet population with which spacecraft data will be compared. Long slit spectra and direct images of all observable comets ( $M_2 < 18$ ) are obtained on a monthly basis (weather permitting) with either a UV sensitive microchannel plate or a red sensitive CCD spectrograph/camera. Scale lengths of the principal emissions of OH, NH, CN, C<sub>3</sub>, C<sub>2</sub>, NH<sub>2</sub> and OI in different comets can be compared. The direct images are used for studies of dust anisotropy which can provide data on the spin vector and gross surface morphology.

This years effort focussed on comets Giacobini-Zinner and Halley in support of the International Halley Watch and the various flight projects. As part of the IHW, a CCD spectrograph/camera was designed and built in time for the P/Giacobini-Zinner flyby. Because of its superior photometric response and on-line reduction and image processing capability, the CCD is now the primary instrument of this project. Spectra and/or direct images were also obtained for comets Wolf-Harrington (1984q), Shoemaker (1984s, 1984f), Schwassmann-Wachmann 1, Arend Rigaux (1984k), Tsuchshan (1984p), Maury (1985k), Giclas (1985g), Ciffreo (1985p) (very interesting coma morphology, IAU 4158), Thiele (1985m) and Boethin (1985n). Preperihelion data was obtained with the CCD on 1.5m and 0.5m telescopes near Tucson on 65 of 76 possible nights during the mid-November through late-January preperihelion period. A three month expedition to the Boyden Observatory in South Africa is currently underway while Comet Halley is at high southern declinations. So far, the weather has permitted about 65% coverage on the dust distribution in the coma since late February. A postperihelion increase in dust production was accompanied by spectacular jet structures. The attached example of CCD spectra show the pre- and post-perihelion changes in continuum (dust) level. The CCD sensitivity has permitted obtaining simultaneous band strengths for both the blue and red CN bands for the first time.

CCD data on Comet Halley so far consists of over 3000 images and spectra with excellent time coverage. Correlation between brightness outbursts, dust jets, and gas emission strengths will be made as well as continued observations of other comets to increase the sample. Reduction of the backlog of comet spectra will continue as possible within the manpower constraints but aided by further software improvements.

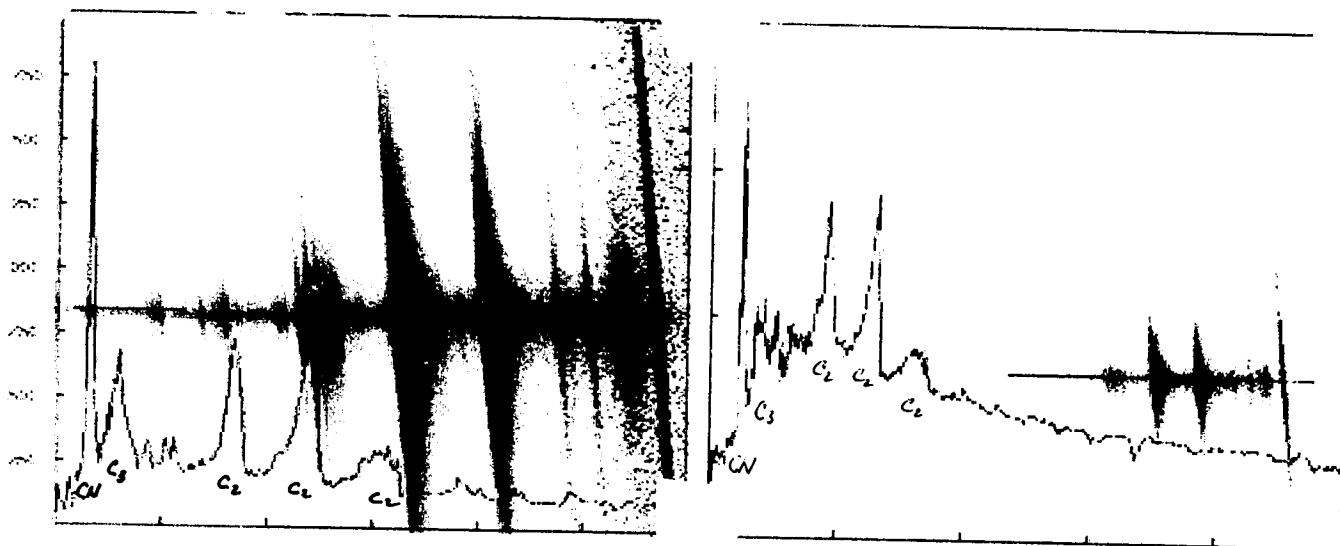
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CCD spectra of Comet Halley taken on 1986 January 6.2 UT (left, preperihelion) and on March 3.1 UT (right, postperihelion) showing the increase in dust after perihelion. The wavelength scale (which increases to the right) differs by a factor of two, but both have the same original dispersions (10 Angstroms/pixel) and similar linear scales (0.75 and 0.64 arcsec/pixel).

INFRARED OBSERVATIONS OF PLANETS

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Co-Investigators: George H. Rieke

a) Our primary objective in this proposal is to carry out a program of near- and thermal-infrared observations of small bodies in the solar system, with the goal of understanding the mineralogy and surface thermal properties of these objects. We intend to concentrate our work on studies that are:

- 1) Relevant to ongoing NASA programs such as IRAS asteroid data analysis.
- 2) Related to future NASA missions such as Galileo and CRAF.
- 3) Related to potential NASA missions such as asteroid missions.
- 4) Targets of opportunity such as the Pluto mutual events.

b) Within the last year, we have published 8 papers on various aspects of our IR studies of comets, asteroids, and satellites. These are listed below in d. Work that has just been completed or is nearing completion includes:

- 1) Water of hydration on asteroids. We have found (Feierberg et al., 1985) a positive correlation between the strength of the 3-micron "water" feature and the strength of the absorption feature shortward of 0.4 microns. This is similar to what is seen in laboratory spectra of carbonaceous chondrites whose silicate compositions range from hydrated phyllosilicates to anhydrous olivine. Our recent work on the so-called ultraprimitive T, P, and D asteroids has shown that absorptions at 3 microns due to water of hydration appear to be present in the spectra of some of these asteroids, but their strengths are less than or equal to those of typical C asteroids. This seems to be inconsistent with the hypothesis that these asteroids are some kind of ultraprimitive low-temperature assemblage, presumably having a higher water abundance than C asteroids.
- 2) Dust trails in the orbits of periodic comets. We have found (Sykes et al., Science, in press) features in the IRAS images that appear to be related to solar system objects. Analysis of the data has yielded narrow trails of dust coincident with the orbits of comets Temple 2, Encke, and Gunn. Dust is found both ahead and behind comet orbital positions due to low-velocity ejection of large particles during perihelion passage. More than 100 additional dust trails are suggested, almost all near the detection limit of IRAS. Many of these dust trails may be derived from previously unobserved comets.
- 3) Asteroid diameters, thermal IR observations of asteroids and a refined standard thermal model for asteroids. We have used the occultation diameters of Ceres and Pallas (obtained by us and others) to improve the "standard thermal model" used in the reduction of thermal IR observations of asteroids. The goal of this program is two-fold: a) to develop a model that can be used for ground-based observations; and b) to develop a simple model that can be used in the preliminary reduction of the IRAS data set which includes 10- to 100-micron

observations of thousands of known and tens of thousands of previously unobserved asteroids.

c) Our principal research areas for the next year are:

- 1) Continued studies of the reflected and thermal IR (1-20 microns) properties of asteroids. This includes looking for water of hydration and carbonaceous material in the 2- to 4-micron spectra and continued studies of the thermal properties of asteroids. Our emphasis will be on potential CRAF and Galileo targets, near-earth asteroids, and asteroids of interest from IRAS studies.
- 2) Participation in occultation experiments for the study of asteroids and planetary satellites and rings.
- 3) Continuation of the refinement and improvement of our thermal models, using new groundbased data and coupled with spacecraft data and occultation results.
- 4) Participation in the observation of the mutual events of Pluto and Charon in the near IR to look for surface compositional variations on Pluto and to try to determine the surface composition of Charon.

d) PUBLICATIONS

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4. Physical parameters of near-Earth asteroid 1982 DV, F. Vilas, D.J. Tholen, L.A. Lebofsky, H. Campins, G.J. Veeder, R.P. Binzel, and A.T. Tokunaga, Icarus **63**, 201-205, 1985.
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7. The dust coma of periodic Comet Churyumov-Gerasimenko (1982 VIII), M. S. Hanner, E. Tedesco, A.T. Tokunaga, G.J. Veeder, D.F. Lester, F.C. Witteborn, J.D. Bregman, J. Gradie, and L. Lebofsky, Icarus **64**, 11-19, 1985.
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ASTEROID TEAM

Principal Investigator: D. L. Matson  
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Co-Investigators: none

**OBJECTIVES:** The purpose of this task is to support asteroid research and the operation of an Asteroid Team within the Earth and Space Sciences Division at JPL. The Asteroid Team carries out original research on asteroids in order to discover, better characterize and define asteroid properties. This information is needed for the planning and design of NASA asteroid flyby and rendezvous missions. The Asteroid Team also provides scientific and technical advice to NASA and JPL on asteroid related programs.

**PROGRESS:** 1) Work on asteroid classification continued and was rewarded with the discovery of two Earth-approaching "M" asteroids. The M class is rare and these are the first found among the near-Earth asteroids to have the spectral albedo characteristic of this class. The two asteroids are newly discovered 1986 DA and 1986 EB which were observed at N and Q bandpasses (i.e. 10 and 20 microns) with the 3 m IRTF telescope and at five wavelengths from 0.36 to 0.85 microns from Kitt Peak National Observatory's 0.36 m telescope. The derived diameters are about 2 km for both objects. 2) In the asteroid radiometry program we obtained N or Q photometry for more than 40 asteroids in Feb. '86. 3) We provided radiometric diameter calibration support for stellar occultations of stars by 230 Athamantis (in Sept. '85) and 129 Antigone (Apr. '85). The data were reduced but not analyzed. 4) Infrared spectra (0.8 to 2.6 microns) of 60 asteroids were reduced and are now ready for compositional analysis. 5) This task supported D. Matson's participation in the NASA Planetary Astronomy Management and Operations Working Group.

**PROPOSED WORK:** Over the next year the work on asteroid classification and composition will continue with the analysis of the 60 reduced infrared spectra which we now have at hand. The radiometry program will continue with the reduction of the N and Q bandpass data for 57 asteroids in order to obtain albedos and diameters. As in previous years we plan to give top priority to any opportunities for observing near-Earth asteroids and the support (through radiometric lightcurve observations from the IRTF) of any stellar occultations by asteroids for which occultation observation expeditions are fielded.

**SUMMARY BIBLIOGRAPHY:** Brown, R.H. (1985). Ellipsoidal Geometry in Asteroid Thermal Models The Standard Radiometric Model, Icarus 64, 53-63. 2) 3 abstracts.

ASTROMETRIC OBSERVATIONS OF COMETS AND ASTEROIDS AND  
SUBSEQUENT ORBITAL INVESTIGATIONS

Principal Investigator: R. E. McCrosky  
Smithsonian Astrophysical Observatory  
Cambridge, MA 02138

Co-Investigators: B. G. Marsden

(a) Objectives

Observations are made of comets and minor planets for the purpose of determining accurate astrometric positions. The positions thereby obtained are used for orbital computations. These computations are necessary if any kinds of further observations, from the ground or from space, are to be made of the objects concerned. The computations are also important for any statistical study of the nature, origin and evolution of these classes of objects, and in the case of comets they shed light on physical processes occurring in these objects.

(b) Accomplishments

During the past year some 500 observations were made on 66 nights and published on the MPCs (Minor Planet Circulars/Minor Planets and Comets); a few of the most urgent ones were also published on the IAUcs (IAU Circulars). In addition, a handful of measurements of earlier plates were completed and published. 121 of the observations published referred to comets. Of special importance were observations of comets (P/Giacobini-Zinner and P/Halley) in connection with the NASA ICE and ESA Giotto missions, but a special effort was made to get good coverage of almost all of the observable comets. Observations were also made of (2060) Chiron and of the earth-approaching objects (1627) Ivar, (1866) Sisyphus, (1943) Anteros, (3362) 1984 QA, 1985 JA, PA, TB and WA, and 1986 DA and EB. 46 minor planets were given permanent numbers entirely as a result of our observations.

(c) Proposed research

Direct photographic observations are made with the 1.5-m reflector at the Oak Ridge Observatory. The emphasis is on faint or unusual objects, but attention is also given to newly discovered objects. Observations are expected to continue much as usual as occasion demands. Orbit computations, ranging from preliminary computations for new objects, through rigorous least-squares differential corrections, including considered of planetary perturbations and (for comets) nongravitational effects, will also be made as appropriate.

(d) Publications

Observations have been published during the past year on 52 Minor Planet Circulars and 14 IAU Circulars. Orbits are on 139 MPCs and 31 IAUcs. As far as observations are concerned, the MPCs have been declared a refereed journal, and observations from Oak Ridge plates are contained on MPC Nos. 9718-9722, 9740-9741, 9813-9815, 9817, 9823, 9845-9846, 9945-9946, 9986, 9988-9989, 9991, 9994, 10021, 10068-10070, 10077-10080, 10108, 10201, 10209, 10223-10226, 10285-10286, 10344-10345, 10359, 10373-10374, 10467-10468, 10504-10506, 10591-10592 and 10605-10606.



PLANET-CROSSING ASTEROIDS - INTERRELATIONSHIPS  
WITHIN THE SOLAR SYSTEM

Principal Investigator: Lucy-Ann McFadden  
 Astronomy Program  
 University of Maryland  
 College Park, MD 20742

Co-Investigators: Michael F. A'Hearn

a. Objectives: This observing program will provide basic information on the mineralogic composition of selected planet-crossing and inner belt asteroids. With this information it is possible to explore the interrelationships of these asteroids with other asteroids, meteorites and comets on the assumption that a possible genetic relationship exists between bodies of similar mineralogic composition. Whereas, mineralogic similarity cannot prove a genetic relationship, certain compositional relationships among objects can be used to rule out the possibility of a genetic relationship. A number of dynamically based models will be tested with these experimental results which will be based on the interpretation of ground-based reflectance spectra. There are dynamical arguments suggesting that some asteroids might be extinct comets. Another phase of this program is aimed at determining the physical properties of extinct comets and whether or not the asteroids in question have physical characteristics which would support the dynamical arguments linking them with comets.

b. Accomplishments: New proposal. We have acquired near-infrared reflectance spectra (0.6-2.5  $\mu\text{m}$ ) of asteroids 1627 Ivar (Amor), 43 Ariadne, 335 Roberta, 386 Siegena and 695 Bella (3:1 Kirkwood Gap) with the IRTF, Mauna Kea. CCD spectra (0.5-1.0  $\mu\text{m}$ ) were acquired of 1866 Sisyphus (Apollo), 17 Thetis, 695 Bella, 797 Montana, and 877 Walkure (3:1 Kirkwood Gap) in collaboration with Dr. Faith Vilas using facilities at Cerro Tololo Inter-American Observatory. An upper limit (3 $\sigma$ ) on the production rate of CN in asteroid 3200 Phaeton of  $< 4 \times 10^{23} \text{ sec}^{-1}$  was determined based on photometric measurements at 3871Å in collaboration with M. F. A'Hearn and R. L. Millis using facilities at Lowell Observatory. This value is in the range of the lowest production rate measured for a comet, however, it does not constitute a positive detection of CN in this asteroid. A first attempt to look for companion objects or evidence of dust debris associated with this asteroid was made with a CCD camera (in collaboration with G. E. Danielson at Palomar Observatory). Whereas the search extended to 19th magnitude (corresponding to 150m and 330m for albedos of 0.15 and 0.03 respectively), we were not able to look close enough to the asteroid to definitively eliminate the presence of co-orbiting dust debris.

c. Proposed Research: We will acquire reflectance spectra of planet-crossing asteroids of high eccentricity and inclination which are likely to have a dynamical relationship to comets. The mineralogy of these asteroids will be compared to that of other planet-crossing and main belt asteroids to look for compositional differences which correlate with

their orbital characteristics. At the same time, we will relate these results to the limited available knowledge of the physical properties of comets as part of the effort to test the proposed genetic relationship between some planet-crossing asteroids and comets. Observations to characterize the physical properties of low-activity, comet nuclei will continue in collaboration with M. F. A'Hearn. Efforts to detect physical properties which are diagnostically comet-like in certain asteroids will continue.

Wetherill (Meteoritics, 20, 1, 1985) has determined the orbital characteristics of meteorites derived from fragmented asteroid material injected into the 3:1 Kirkwood Gap using Monte Carlo techniques. The predicted orbits closely match those of the ordinary chondrite meteorites. Observations of reflectance spectra of asteroids near the 3:1 Kirkwood Gap will determine the compositional relationship between these asteroids and ordinary chondrites. Based on the chemistry of the pyroxene mineralogy, we should be able to establish the plausibility of the presence of material of ordinary chondritic composition. Current interpretations of S-type asteroids which conclude that they are ordinary chondrite analogues (e.g. Feierberg et al. Ap.J. 257, 361, 1982) have been disputed by more rigorous interpretation (e.g. Gaffey, Icarus, 60, 83, 1984). Additional experimental data of sufficient spectral resolution are needed to quantitatively interpret spectra of asteroids near the 3:1 Kirkwood Gap (i.e. determine the chemical mineralogy of pyroxene which is tightly constrained in ordinary chondrites). This will permit addressing the fundamental question of the location of meteorite sources with another technique which is completely independent of the orbital dynamics approach.

OCCULTATION STUDIES OF THE SOLAR SYSTEM

Principal Investigator: Robert L. Millis  
Lowell Observatory  
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Co-Investigators: Lawrence H. Wasserman  
Edward L. G. Bowell  
Otto G. Franz

(a) The primary scientific objectives of this research program are to directly determine sizes and shapes of a representative sample of asteroids, to determine the mean densities of Ceres, Pallas, and Vesta to an accuracy that is diagnostic of composition, and to directly measure the radial distribution and albedo of grains in cometary comae. Accurate asteroid dimensions and shapes are needed to permit better thermal modelling of asteroids and to allow full interpretation of radar data. Knowledge of the distribution of grains in the coma of a comet will usefully constrain cometary models while a well-determined grain albedo will provide a clue to the composition of cometary "dust." Secondary objectives include refinement of Galilean satellite orbits through observation of mutual events, and investigation of planetary ring systems.

(b) Recent accomplishments under this grant include determination of the size, shape, mean density, and albedo of Ceres. Predictions for 133 occultations of bright stars occurring in 1986 and 1987 have been completed and published this year, as have predictions of occultations of stars by Comet Halley. Twenty-nine mutual events involving Galilean satellites were observed at Flagstaff in 1985. A paper discussing our observations of the 22 April 1982 occultation of a star by Uranus and its rings has been completed and submitted for publication.

(c) During the coming year we intend to observe occultations of stars by selected asteroids including Europa, Euterpe, Papagena, and Alexandra. A lengthy paper discussing the important results for Ceres from the 13 November 1984 occultation will be published. We also expect to publish the results of observations of recent occultations by Aglaja and Antigone. A catalog search for occultations of stars by asteroids in 1988 and 1989 will be completed and predictions published. Additionally, Millis, in his new role as chairman of the IAU Commission 20 Working Group on Occultations, will be striving to better organize occultation research activity on a global scale.

(d) Recent Refereed Publications.

- Aksnes, K., Franklin, F., Millis, R., Birch, P., Blanco, C., Catalano, S., and Piironen, J. (1984). Mutual phenomena of the Galilean and Saturnian satellites in 1973 and 1979/80. *Astron. J.* 89, 280-288.
- Bowell, E., Wasserman, L. H., Baum, W. A., Millis, R. L., and Lumme, K. (1984). Occultations of stars and radio sources by comets: Predictions and observing prospects. In *Cometary Astronomy* (D. Yeomans, R. West, R. Harrington, and B. Marsden, eds.), pp. 105-122.
- Millis, R. L. (1986). Occultation studies with small telescopes. In *Proceedings, IAU Symposium No. 118* (J. B. Hearnshaw and P. L. Cottrell, eds.). D. Reidel Publishing, Netherlands.
- Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Klemola, A., and Dunham, D. W. (1984). The diameter of 375 Ursula from its occultation of AG+39°303. *Astron. J.* 89, 592-596.
- Millis, R. L., Wasserman, L. H., Franz, O. G., Bowell, E., and Klemola, A., (1984). Occultations of stars by solar system objects. V. A photographic search for occultations by selected asteroids in 1984. *Astron. J.* 89, 698-701.
- Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Nye, R., Osborn, W., and Klemola, A. (1985). The occultation of AG+29°398 by 93 Minerva. *Icarus* 61, 124-131.
- Wasserman, L. H., Bowell, E., and Millis, R. L. (1985). Occultations of stars by solar system objects. VI. Occultations of catalog stars by asteroids in 1986 and 1987. *Astron. J.* 90, 2124-2129.

PHOTOMETRY OF COMET HALLEY

Principal Investigator: John S. Neff  
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University of Iowa  
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Co-Investigators: Tracy A. Ellis

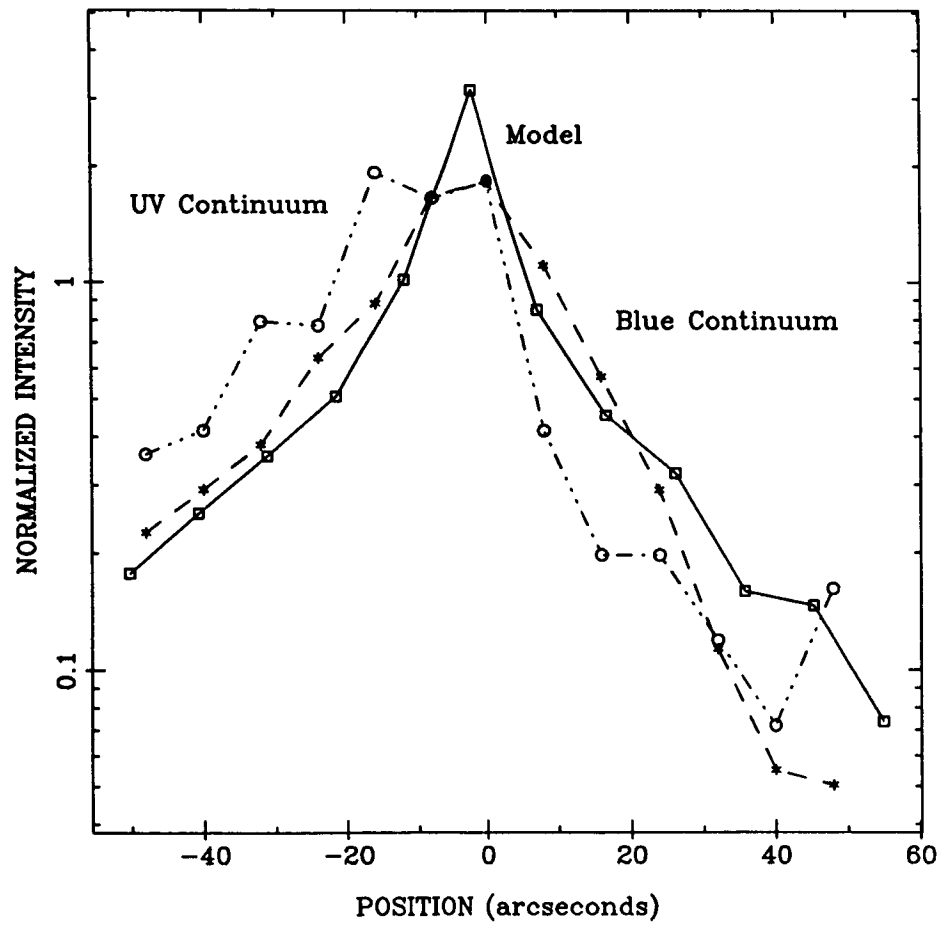
The objectives of this study were to obtain intensity profiles of Comet Halley using the IAU filter set and the scanning photometer on the telescope at the University of Iowa Observatory, to develop models for the dust and gas emission from the nucleus of the comet, and use these models to compute synthetic spectra for comparison with the observations.

This is a new proposal. At the time of this writing we have been able to obtain observations of Comet Giacobini-Zinner on one night and of Comet Halley of three nights. When the comet becomes high enough we hope to obtain further observations of Comet Halley.

Considerable progress has been made in developing a probabilistic model for the emission of neutral dust by the nucleus of the comet. A preliminary comparison between the model and the observed intensity profiles in continuum filters is made in the attached figure. The model can also be used to compute the expected impact rates of dust on spacecraft flying past the comet.

When the model for the continuous spectrum of the comet is complete we will start to compute the emission band spectrum of the comet for comparison with the measurements made with the other filters. We also intend to investigate the problem of the motion of charged dust particles in collaboration with C. Goertz.

P/HALLEY (1/6/86)



PHYSICAL PROCESSES IN COMETS

Principal Investigator: Ray L. Newburn, Jr.  
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California Institute of Technology  
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Co-Investigators: none

a. Objectives

The objectives of this work unit are to make quantitative observations of the physical properties of comets, to determine from them the behavior of the gases and dust in each object studied, and to derive improved models of the cometary nucleus from that behavior. Comets vary greatly one from the other in dust-to-gas ratio and in the relative abundance of gases, as well as in absolute activity. A given comet shows great change with heliocentric distance, as well as changes from apparition to apparition. The full range of cometary behavior must be understood, if maximum value is to be obtained from spacecraft studies, and if suitable models are to be prepared for spacecraft design.

b. Accomplishments

Final revisions were made in the study of continuum spectrophotometry of 17 comets done at Lick Observatory. The paper was accepted for publication. Changes based upon this study were introduced into the Divine-Newburn cometary modelling paradigm. The entire modelling approach was written up and accepted for publication. Work was begun on modifications to all of the theory based upon the direct nucleus and coma observations made by the Halley space missions.

c. Proposed Research

A paper will be prepared for the Heidelberg Comet Conference on the changes in cometary modelling techniques introduced by the facts gathered during the Halley encounters. These modifications will be applied to reanalysis of the 120 IDS scans taken on 17 comets from Lick Observatory with the new results presented as paper III in the series. Analytic techniques for analysis of two dimensional CCD filter photometry and rectangular slit CCD spectrophotometry will be studied in preparation for analysis of new Halley data. Halley itself will be followed until all signs of activity have ceased.

d. Publications

Newburn, R. L. Jr. & Spinrad, H., "Spectrophotometry of Seventeen Comets. II. The Continuum," Astron. J. 90, 2591-2608, 1985.

Divine, N., Newburn, R. L. Jr., et al, "The Comet Halley Dust and Gas Environment," Space Sci. Rev. 43, 1-104, 1986.

#### Proposed Research for 1986:

1. We are continuing a program of CCD imaging of Comet Halley begun in 1985. Although capital costs of the equipment were funded by JPL through the IHW, no funds were provided for testing or use of the instrument. The instrument was developed in collaboration with S. Larson and is being used every clear night - first from Mauna Kea, then Lowell Observatory and now Perth Observatory. Narrow-band images will be used to derive molecular production rates, map spatial distributions of neutrals and ions, monitor both short term and long term fluctuations in these species, and study the distribution of dust. Spectra will also be obtained with this instrument and it will be used to monitor possible occultations in April of 1986.
2. Photometry of comets Giacobini-Zinner and Halley will be analyzed in collaboration with Millis and Schleicher and probably others for comparison with spacecraft data as well as for studies of the physical nature of these two comets, each of which is very unusual in one or more respects.
3. We hope to analyze our complete data base of photometric data to better understand the systematics of radical production from comet to comet. The study of NH is already underway but most of this analysis must await the completion of observations of Halley.
4. Our calculations of theoretical spectra has been extended to include collaboration with C. Arpigny of Liege and we are currently comparing our calculated spectra of  $\text{CO}^+$  with a series of cometary spectra. When this is complete we will initiate a study of CH together with Arpigny. It is expected that this effort will be separately supported by 1987.

#### Publications:

- M. A'Hearn, 1986, Are Cometary Nuclei like Asteroids? Asteroids, Comets and Meteors II ed, Lagerkvist et al. Reprocentralen, HSC, Uppsala, Sweden, pp. 187-190.
- M.F. A'Hearn, P.V. Birch, P.D. Feldman and R.L. Millis, 1985, Comet Encke: Gas Production and Light Curve, Icarus 64, 1-10.
- M. A'Hearn, D. Schleicher and R.A. West, Emission by OD in Comets, 1985, Ap.J. 297, p. 826-836.
- H. Campins, M.F. A'Hearn and L.A. McFadden, 1986, The Nucleus of Comet Neujmin-1, (in prep).
- M. A. Coplan, K. W. Ogilvie, M. F. A'Hearn, P. Bochslers, and J. Geiss, 1986, Observations of Ion Composition and Velocity Distributions at Comet P/Giacobini-Zinner (in prep).
- L. Magnani and M.F. A'Hearn, 1986,  $\text{CO}^+$  Fluorescence in Comets, Ap.J. 302, 477-487.
- R. L. Millis, M. F. A'Hearn and H. Campins, 1986, The Nucleus and Coma of Comet Arend-Rigaux (in prep).



STUDY OF COMETS AT WAVELENGTHS BETWEEN 0.5 AND 18 MICRONS

Principal Investigator: Edward P. Ney  
 Department of Astronomy  
 University of Minnesota  
 Minneapolis, MN 55455

Co-Investigators: Robert D. Gehrz

a) Objectives. The O'Brien telescope has been used for fifteen years to study bright comets with filters of  $\lambda/\Delta\lambda \approx 10$  at wavelengths between 0.5 and 18 microns. The objective of the study is the understanding of the role of the grains in determining the reflected and thermally reradiated energy from comet comae, tails and sunward spikes (anti tails). Ultimately one hopes to determine the relative importance of silicate grains, carbonaceous materials and ice. Both the size distribution and the composition of the grains contribute to the energy distribution we observe. Cometary grains represent the only astrophysical dust sample which can be studied with known geometry. This is because the dusty region is relatively small and has a well determined geometry. (The distances from the earth and sun are known and so is the scattering angle.)

The silicate feature discovered in Comet Bennett's coma has made it possible to detect the presence of optically thin small silicate grains in the comae and tails of dusty comets and to relate the strength of the silicate signature to the comet morphology.

b) Accomplishments. Since 1969 we have measured every bright comet which has reached a distance of one astronomical unit from the sun. We have developed observing techniques which make it possible to observe as close as elongation  $3^\circ$ , and to find, track and measure comets at all wavelengths in full daylight. We measured Comet Halley on twenty four occasions between December 12, 1985 and March 25, 1986. Clear weather seems to come on holidays, and days on which we observed included Winter Solstice, Christmas, New Years, Valentines day, Super Bowl Sunday and the Vernal Equinox. We observed Halley within hours of perihelion passage.

Important accomplishments have included:

1. The silicate signature in Comet Bennett (Paper 1).
2. The superheat of small grains caused by their low emission efficiency when their size is comparable to the wavelength at which they emit their thermal radiation (Paper 2).
3. The absence of the silicate signature in the "anti tail" grains of Comet Kohoutek suggesting that these grains are large ( $r \approx 1$  millimeter) as predicted by Zdenek Sekanina (Paper 3). The large grains or rocks chip off from the nucleus and take on orbits similar to the orbit of the comet. These "rocks" are responsible for the meteor showers associated with comets. For Halley these would be the Orionids and the Eta Aquarids. The difference between large and small grains is shown in Figure 1. This figure also shows the clear separation of reflected sunlight and thermal reradiation.
4. The scattering function of cometary coma grains. Comet West passed between the earth and the sun as did 1980t. Their geometry made it possible to show that the grains have a very strong forward scattering function as expected for 1 to 2 micron diameter dielectric grains (silicates and ice?). Comet Halley was observed at backscattering angles out to 165 degrees. Any backscattering increase is small or absent (Figure 2 and Paper 4).

5. The relative emission of thermal radiation and its variation with solar distance for many comets. A first approximation for the activity index for comets makes the radial variation of energy absorbed and re-emitted proportional to  $1/r^4$ . Eight comets are shown in Figure 3. There are great variations from the canonical  $1/r^4$  presumably caused by rotation of the nucleus presenting active and passive surfaces to the sun. The quantity  $(\lambda F_\lambda)_{\max}$  for the thermal emission is a measure of the energy radiated, and is equal to the energy absorbed. This should be a better measure of a comet's intrinsic brightness than short wavelength reflected light measurements because of the variation in albedo.
  6. The large day to day variations in the brightness of Comet Halley. Figure 3 shows Comet Halley compared to some other comets. Halley can vary in brightness by a factor of ten, and its thermal emission can be as dim as Kohoutek or as bright as Bennett or West. We will study this large variability and compare it with Sekanina's predictions which are based on photographs which show the emission by active regions. Figure 4 shows an example of O'Brien data on Halley taken 3 days post perihelion. The solar elongation angle was 12 degrees.
  7. Small dust and large dust comets. It appears that new comets usually have large "dust bumps" at ten and twenty microns. This is taken to indicate that 1 to 2 micron grains are present. Some new comets (Kobayashi Berger Milon) and most periodic comets (except for Halley) show black body energy distributions like the "anti tail" of Comet Kohoutek. We believe that processed comets have blown off their small dust grains (at least the silicate grains).
  8. Observations at WIRO and O'Brien. R. D. Gehrz has succeeded in using the WIRO Wyoming telescope in a remote observing mode. By using three telephone lines he can command the WIRO computer run telescope from a station at the University of Minnesota. The data output is received as the observations are being made. The observing plan may be altered as the data are acquired just as one would do at the telescope. Gehrz had twelve successful observing runs between January 12 and March 14. Two of these were simultaneous with O'Brien observations. The comet is on the meridian about an hour later at Wyoming than at O'Brien so extended observing runs can be accomplished.
  9. Using infrared observations to predict the optical depth of Halley's coma. Sending missions to photograph comet nuclei could be a failure if the dust cloud were thick enough to obscure the nucleus. (It would be like trying to photograph a house in a snowstorm.) We used our observations to make a semi-empirical theory which predicted that the dust cloud around Halley would be optically thin. Paper 5. The extraordinary Giotto mission results indicated that these predictions were correct. Several copies of paper 5 are included with this document.
- c) Proposed Research. We would like to continue these observations as new comets come along. We believe it is important to understand the variation in the strength of the silicate features which range from very strong in Comet Bennett to medium in Comet Halley to muted or missing in Comet Kobayashi Berger Milon. The albedo of the grains varies by a factor of more than ten. This probably represents a change in the ratio of carbonaceous to silicate materials. Observations of comets over a range of scattering angles, especially at angles less than  $30^\circ$  and greater than  $165^\circ$ , would complete the curve of Figure 2 and present a challenge to fit it with theoretical models.

We hope to obtain narrow band  $\frac{\lambda}{\Delta\lambda} > 100$  observations of the 10 and 20 micron features in future comets.

We propose to collect all of the data that exist which bear on the albedo question and to present the observations in a unified form which will show the dependence of the albedo on any other comet characteristics such as strength of the silicate signature and grain superheat.

We also will try to exploit the simultaneous observations at O'Brien, WIRO, and Mt. Lemmon. The diverse characteristics of the instrumentation associated with these facilities should allow a large variety of observational configurations of this array of telescopes.

d) Publications.

Paper 1. "The 10-Micron Emission Peak of Comet Bennett 1969i," R. W. Maas, E. P. Ney and N. J. Woolf, 1970, Ap. J. 160, L101.

Paper 2. "Infrared Observations of Comet Kohoutek Near Perihelion," E. P. Ney, 1974, Ap. J. 189, L141.

Paper 3. "Optical and Infrared (.5 $\mu$  to 20 $\mu$ ) Observations of Bright Comets," E. P. Ney, 1981, IAU Colloquium No. 61, University of Arizona Press, 1982.

Paper 4. "Comet West and the Scattering Function of Cometary Dust," E. P. Ney and K. M. Merrill, 1976, Science 194, 1051.

Paper 5. "The Visibility of Comet Nuclei," E. P. Ney, 1982, Science 215, 397.

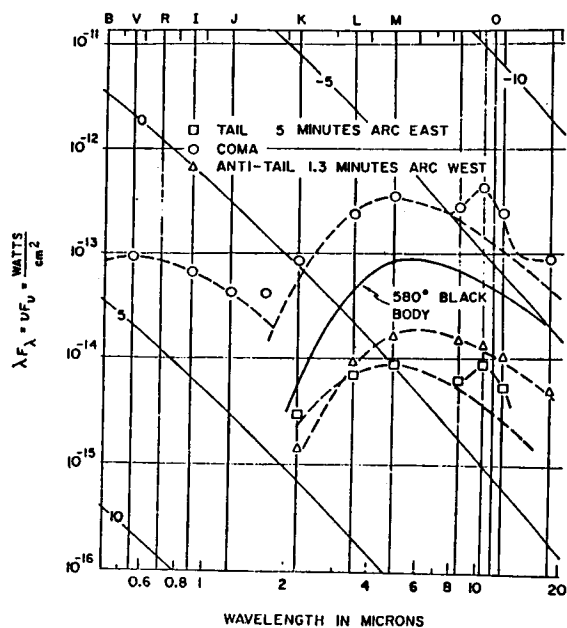


Figure 1: The spectral energy distributions of the coma, tail, and anti tail of Comet Kohoutek showing the differentiation of the spectra produced by large (anti-tail) and small (coma and tail) cometary dust grains.

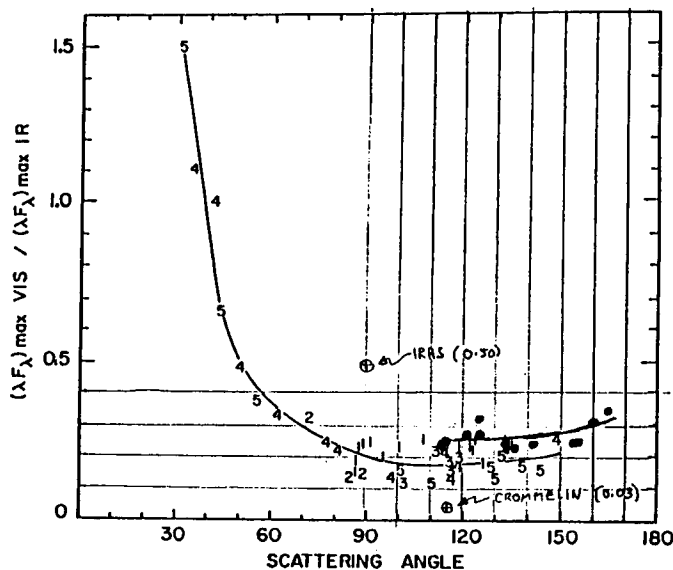


Fig.2. The ratio of reflected to absorbed energy for five comets of this survey. Identifications are: 1 = 1973 XII; 2 = 1974 III; 3 = 1975 IX; 4 = 1976 VI; 5 = 1980 I. • HALLEY

### III. THE INFRARED BRIGHTNESS OF COMETS AS A FUNCTION OF HELIOCENTRIC DISTANCE

Figure 3 shows the energy radiated by seven comets. These data are corrected to an Earth-comet distance of 1 AU. Most of the curves are near the canonical  $1/r^2$  slope indicating a  $1/r^2$  dependence of dust production. Two comets show an abrupt increase in brightness at the time of fragmentation; Comet Bradfield 1974 III, shows an abrupt drop in dust production, and

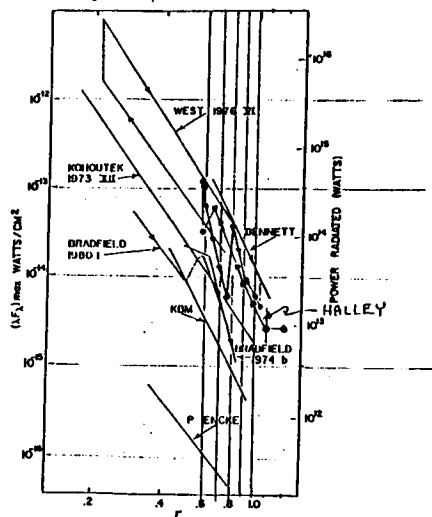
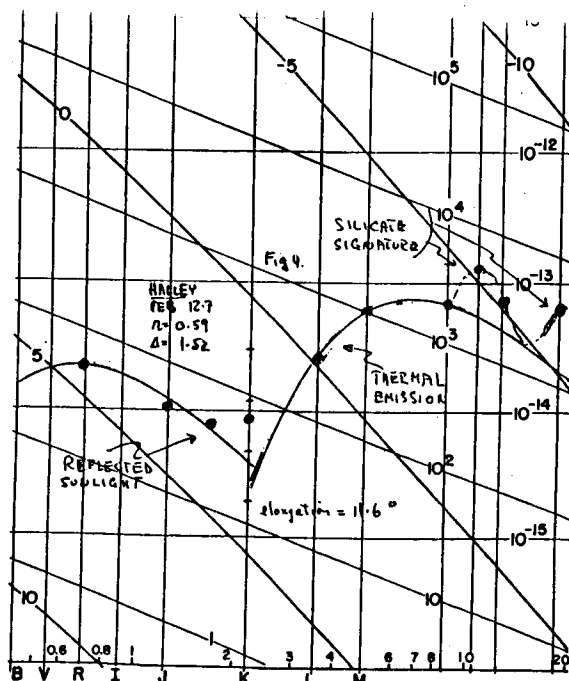


Fig. 3. Power radiated as a function of heliocentric distance for seven comets.



RADAR INVESTIGATION OF ASTEROIDS

Principal Investigator: Steven J. Ostro  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: none

Objectives: The goal of this research is ground-based radar reconnaissance of asteroids. The principal investigator conducts 13-cm observations at the Arecibo Observatory (NAIC) and 13.5-cm observations with the NASA/JPL Goldstone Solar System Radar. Investigated objects represent the two major dynamical populations of minor planets: Earth-approaching objects with diameters  $< 10$  km and much larger objects in the main asteroid belt between Mars and Jupiter.

Radar observations achieve spatial resolution of a planetary target in a manner that is independent of the target's apparent angular size and hence provide a powerful groundbased tool for investigating asteroids, which generally remain unresolved by optical telescopes. Furthermore, by virtue of the wavelengths employed, radar can furnish unique information about (i) surface structure at scales much larger than typical asteroid dimensions; and (ii) compositional parameters (e.g., volume fractions of metal, rock, and vacuum) that are only weakly constrained by VIS/IR methods.

Primary scientific objectives include estimation of echo strength, circular polarization ratio ( $\mu_c$ , of echo power received in the same sense of circular polarization as transmitted to that in the opposite sense), spectral bandwidth, spectral shape, Doppler shift, and echo time delay. These measurements provide information about asteroid size, shape, spin vector, surface structure at cm-to-km scales, and regolith bulk density, porosity, and metal concentration. The observations also can refine our knowledge of the target's orbit, a capability with greatest potential value for near-Earth asteroids, especially if the observations take place during the discovery apparition.

Accomplishments: During the five years since this program's initiation in 1980, the number of radar detected asteroids has climbed from 6 to 40 (27 mainbelt plus 13 near-Earth). The dual-circular-polarization radar sample now comprises more than 1% of the numbered asteroids.

Radar results for mainbelt asteroids furnish the first available information on the nature of these objects at macroscopic scales. At least one object (2 Pallas) and probably many others are extraordinarily smooth at centimeter-to-meter scales but are extremely rough at some scale between several meters and many kilometers. Pallas has essentially no small-scale structure within the uppermost several meters of the regolith, but the rms slope of this regolith exceeds  $20^\circ$ , much larger than typical lunar values ( $\sim 7^\circ$ ). The origin of these slopes could be the hypervelocity impact cratering process, whose manifestations are likely to be different on low-gravity, low-radius-of-curvature objects from those on the terrestrial planets.

The range of mainbelt asteroid radar albedoes is very broad and implies big variations in regolith porosity or metal concentration, or both. The highest albedo estimate, for 16 Psyche, is consistent with a surface having porosities typical of lunar soil and a composition nearly completely

metallic. Therefore, Psyche might be the collisionally stripped core of a differentiated small planet, and might resemble mineralogically the parent bodies of iron meteorites.

The recent observations of near-Earth asteroids bolster the view that this population is very diverse, presumably because of the variety of these objects' source locations. It now seems well established from polarization-ratio measurements that near-Earth asteroids tend to be significantly rougher than their much larger mainbelt counterparts. This result is consistent with theoretical expectations of thin, rocky regoliths on small asteroids. However, the distribution of these objects' weighted mean values of  $\mu_c$  is extremely broad, and resolution of echo spectra generally reveals significant cm-to-m-scale heterogeneity on target surfaces. The data also provide direct evidence for nonspherical and occasionally very irregular shapes, and reveal a few objects to have peculiar radar signatures. For example, 2101 Adonis's polarization behavior ( $\mu_c = 1.0 \pm 0.2$ ) is not radically different from that of the trailing side of Jupiter's satellite Callisto, but is very different from those of other radar-detected asteroids and active comets.

For a few asteroids (e.g., 1 Ceres, 7 Iris, 2100 Ra-Shalom), echo spectra have been acquired for two oppositions for which the directions of the radar-asteroid vectors were many tens of degrees apart. The resultant pair of bandwidth estimates place especially strong constraints on the target's pole direction. (Radar constraints on pole direction are, in principle, the most reliable obtainable with any groundbased technique.)

Proposed Research: Observations of previously undetected asteroids will be conducted to obtain new information about target physical properties and to clarify the extent to which those properties are correlated with size and composition. A few objects will be reobserved at apparitions which offer substantial improvements in echo strength or novel viewing geometries. Special efforts are planned for potential flyby targets for future space missions (Galileo, CRAF, and NEAR). The 1986-88 target list also includes the near-Earth object 3199 Nefertiti, which is spectrally similar to pallasites and might even be (or share) the parent asteroid of those rare, stony-iron meteorites; 4 Vesta, for which a major objective is to use a precise echo bandwidth measurement to resolve once and for all the controversy over the rotation period; and 1566 Icarus, for which a precise radar range can permit a valuable test of General Relativity. Also, it is anticipated that discoveries of new near-Earth asteroids will provide unforeseen "targets of opportunity" for both Arecibo and Goldstone.

#### Recent Publications:

Mainbelt Asteroids: Dual-Polarization Radar Observations. S. J. Ostro, D. B. Campbell, and I. I. Shapiro. Science 229, 442-446 (1985).

Radar Observations of Asteroids and Comets. S. J. Ostro. Publ. Astron. Soc. Pacific 97, 877-884 (1985).

Physical Properties of Asteroids from Radar Observations. S. J. Ostro. Proceedings of the International School of Physics "Enrico Fermi," The Evolution of the Small Bodies of the Solar System, in press (1986).

GROUND-BASED OBSERVATION OF COMET HALLEY

Principal Investigator: Frank Scherb  
 Department of Physics  
 University of Wisconsin  
 Madison, WI 53706

Co-Investigators: Fred L. Roesler

Objectives.

Our main objectives in our comet Halley program are:

1. To study the interaction of the solar wind with the cometary plasma. The method employed uses a Fabry-Perot spectrometer to obtain high spectral resolution observations of cometary  $\text{H}_2\text{O}^+$  emissions in the coma and along the ion tail during each night of observing. Information about the density distributions, and velocities of the cometary ions is obtained from the intensities, profiles, and Doppler shifts of the  $\text{H}_2\text{O}^+$  emission lines. For example, tailward accelerations of the cometary ions can be obtained from the variation of Doppler shift of the ion emissions along the tail.

2. To measure the production rate of atomic hydrogen over as large a range of heliocentric distances as possible, both pre-perihelion and post-perihelion, from observations of Balmer alpha ( $\text{H}\alpha$ ) emissions from the hydrogen cloud surrounding the comet. The hydrogen production rate can be used to determine the comet production rate of gaseous water ( $\text{H}_2\text{O}$ ). The heliocentric variation of  $\text{H}_2\text{O}$  production rate is an important aspect of the evolution of the comet during its passage through the inner solar system.

3. To measure the production rate of metastable ( $^1\text{D}$ ) oxygen atoms over a large range of heliocentric distances, both pre-perihelion and post-perihelion, from observations of cometary  $[\text{OI}]$  6300 Å emissions. The  $\text{O}(^1\text{D})$  production rate can be compared with the  $\text{H}_2\text{O}$  production rate (obtained from our  $\text{H}\alpha$  observations) to see if the ratio of these rates varies with heliocentric distance. Previous studies have suggested that the ratio seems to be constant in a sample of several comets observed before the present apparition of comet Halley.

4. To compare our values of the cometary  $\text{H}_2\text{O}$  production rate obtained from our  $\text{H}\alpha$  observations with the corresponding rates inferred from satellite UV and ground-based observations of the OH molecule. It will be important to investigate discrepancies that arise among these different techniques for measuring the  $\text{H}_2\text{O}$  production rate.

Accomplishments.

Approximately five hundred Fabry-Perot scans of  $\text{H}_2\text{O}^+$ ,  $\text{H}\alpha$ , and  $[\text{OI}]$  emissions from comets Halley, Hartley-Good, and Thiele have been obtained at Kitt Peak in November, December and January. The analysis of the data is in a very early stage, but preliminary results have been obtained on the production rate  $Q(\text{H})$  of hydrogen,  $Q(^1\text{D})$  of metastable oxygen, and  $Q(\text{H}_2\text{O})$  of water. The rate  $Q(\text{H})$  varied with heliocentric distance  $R$  as  $R$  to the power  $-3.5 \pm 0.5$ . The rate  $Q(^1\text{D})$  varied as  $R$  to the power  $-4.8 \pm 0.1$ . The ratio of  $Q(\text{H}_2\text{O})$  to  $Q(^1\text{D})$  was  $15 \pm 5$ . These results are shown in Figure 1.

We are scheduled to observe comet Halley at Kitt Peak for two weeks in April and two weeks in May. We are planning to add an imaging detector to the Fabry-Perot spectrometer in order to combine spatial imaging with high spectral resolution. This combination will provide information on the spatial distribution of different velocity components of the cometary gases and plasmas.

### Proposed Research.

We plan to continue our observations of comet Halley in April and May, 1986, with the addition of an imaging detector, to be provided by the Lunar and Planetary Laboratory in Tucson. We will also be collaborating with the comet research group at Goddard Space Flight Center in the acquisition and analysis of data from our new imaging Fabry-Perot spectrometer. Thus we are in the process of expanding the scope of our collaborations with other groups. When the observations are completed, we will then devote our efforts to data analysis and active collaboration in the international program of comet Halley studies.

### Publications.

F. Scherb, "Hydrogen Production rates from Ground-Based Fabry-Perot Observations of Comet Kohoutek", Ap. J., 243, 644 (1981).

P. Shih, F. Scherb, and F. L. Roesler, "Hydrogen Production Rate from Comet Austin (1982g)", Ap. J., 279, 453 (1984).

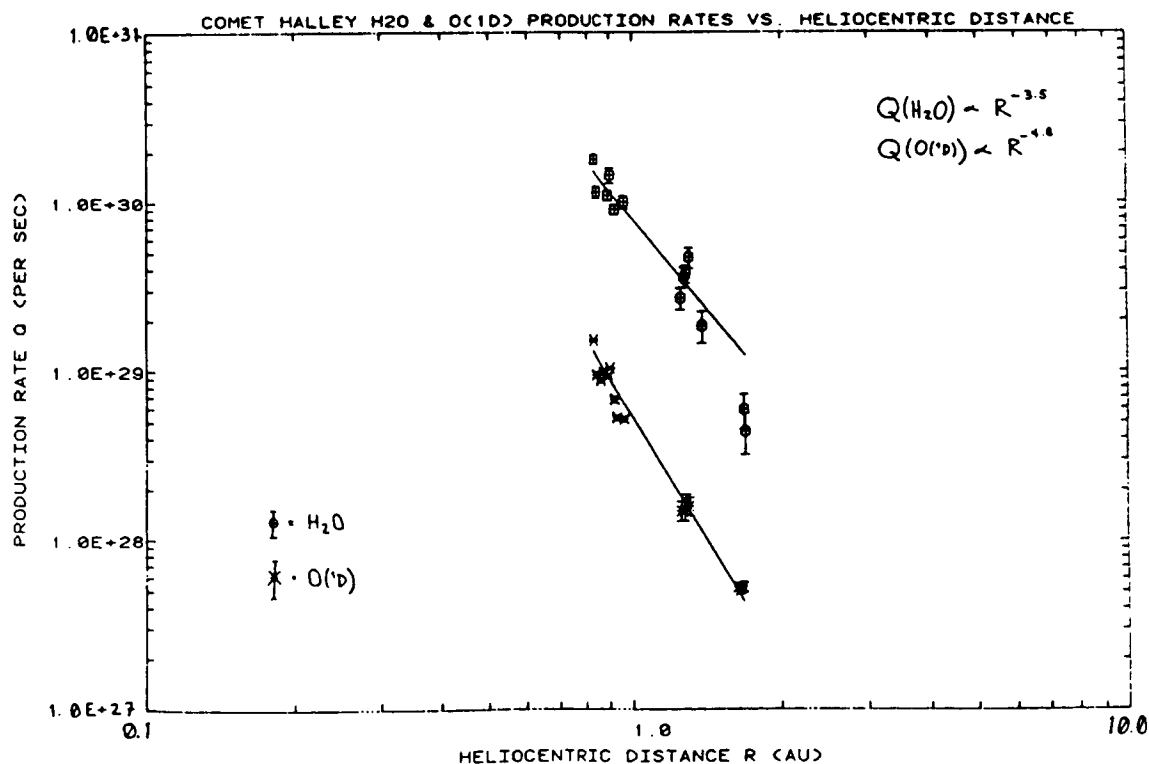


FIGURE 1



RECOVERY OF THE UCAS ASTEROIDS

Principal Investigator: Eugene M. Shoemaker  
U.S. Geological Survey  
Flagstaff, AZ 86001

Co-Investigators: Schelte J. Bus

(a) The goal of this project is to extend the observed arcs of about 500 UCAS (UK-Caltech Asteroid Survey) asteroids to multiple oppositions so that they may be readily recovered for future study. The work is providing a large set of high-precision orbits for very faint asteroids, essential for future physical and orbital studies of these small objects. In particular, the light-scattering and rotational properties of kilometer-size asteroids are essentially unknown. The recovery work is being accomplished by obtaining positions from archival photographic plates taken in years other than that of the original UCAS survey plates (1981), and by targeting CCD astrometric observations of selected UCAS asteroids. Some aspects of the research under this grant have developed from work completed under NAGW-569 and in progress through NSG-7500 at Lowell Observatory.

(b) The main accomplishments thus far include: (1) Completion of the astrometric measurements of the original 1981 UCAS survey plates, leading to a grand total of 1252 orbits for newly discovered asteroids ranging in absolute magnitude from  $H = 10.5$  to 19.5; (2) Creating new programs and revising existing computer routines at Lowell Observatory, which has streamlined the process of correctly identifying asteroid images on archival photographic plates; (3) The recovery and accurate measurements of 130 UCAS asteroids at other oppositions on plates taken by C. T. Kowal at Palomar Mountain in 1978 and 1979. When added to the 90 other UCAS objects identified by other investigators, this brings the total of multiple-opposition orbits to 220; (4) Of the 56 UCAS asteroids known to be planet crossing, 11 have been recovered at second oppositions; (5) The recovery and accurate measurements of about 20 non-UCAS asteroids identified on the plates examined.

(c) Efforts proposed for the duration of this grant include: (1) Continued work with Kowal's Palomar plates, from which evidence exists that images of another 200 UCAS asteroids can be easily identified and measured; (2) Examination of other plates, particularly those taken on the 48-inch Schmidt at Palomar, even though they may not be as well suited to these recovery efforts as Kowal's plates; (3) Measurements will be made of single-opposition non-UCAS asteroids which are found on those plates examined; (4) Astrometric CCD observations will be attempted for selected UCAS objects, especially planet crossers and family members; (5) Trial observations will be made using the Lowell Observatory 72-inch reflector and CCD of a small number of faint UCAS asteroids from which accurate magnitudes and some colorimetric information will be obtained.

(d) Bus, S. J., Helin, E. F., Dunbar, R. S., Shoemaker, E. M., Dawe, J., Barrow, J., Hartley, M., Morgan, D., Russell, K., and Savage, A. (1983). The United Kingdom/Caltech Asteroid Survey. **NASA Technical Memorandum** No. 81527, pp. 53-56.

Bus, S. J. (1985). [Asteroid observations]. **Minor Planet Circular** Nos. 9940, 10236-10270.

Bus, S. J. (1986). [Asteroid observations]. **Minor Planet Circular** Nos. 10368 and 10369.

HIGH RESOLUTION SPECTRAL IMAGERY OF COMETS

Principal Investigator: Wm. Hayden Smith  
 Department of Earth and Planetary Sciences  
 Washington University  
 St. Louis, MO 63130

Co-Investigators: none

## Objective:

To study the isotopic composition of comet Halley to determine the relationship of the formation of this comet to the remainder of the solar system.

## Accomplishments

We have obtained  $^{13}\text{C}/^{12}\text{C}$  data at a spectral resolution of 75,000, resolving the background interferences. Some data has been obtained for  $^{15}\text{N}/^{14}\text{N}$ . In April, we are to obtain observations for the D/H ratio. The model analysis of these observations is beginning with the goal of presentation at the Heidelberg Halley meeting.

## Objective

To study the molecular composition of Halley via the variability of the [O I] features at 6300 and 5577 Å.

## Accomplishments

We have obtained a very large quantity of observations of both features with variations on the time scale of an hour being measured. At times, the 5577 feature dominates, and at times it is nearly absent.

## Objective

To determine the production rate and photochemistry of  $\text{H}_2$  in Halley.

## Accomplishments

Observations for this purpose take place at Mauna Kea on March 25-28.

## Objective

Velocity and abundance measurements for molecular radicals and ions.

## Accomplishments

To date, we have a large body of data for  $\text{C}_2$ ,  $\text{NH}_2$ , [O I], and probably  $\text{H}_2\text{O}^+$ , CN, and from the MKO data, OH. These features can all be correlated with respect their relative velocities and distribution at the time of observation. We anticipate using the Greenstein effect to measure similar results for CN, OH, and a few other selected molecular features.

## Publications

To date, we have not submitted any publications from this research which was begun on 1 Jan. 1986. We do have fully reduced data for p-Giacobinni-Zinner in CN and K I features sought in absorption.

SPATIALLY RESOLVED QUANTITATIVE SPECTROSCOPY OF COMETS

Principal Investigator: Hyron Spinrad  
 Department of Astronomy  
 University of California  
 Berkeley, CA 94720

Co-Investigators: none

a. Objectives

The overall global objective of this research is to learn more about the pristine nucleus of a comet, in particular, its chemical composition. More immediate goals are to quantitatively compare the mass-loss-rates of various periodic comets, and to map out the distribution of coma region ions and neutral radicals with the hope of indirectly determining their parent molecules.

b. Accomplishments

Recent scientific progress, on a small-scale, but with interesting pieces of the bigger picture, continues to be pretty good. We are now preparing a paper on the distribution of the  $H_2O^+$  ions across the tail of P/Giacobini-Zinner during the September 11, 1985 passage of the ICE spacecraft (Strauss, McCarthy, and Spinrad, 1986 -- in preparation, preprint attached). While the cross-cut through the ion tail on our spectrum has projected FW Zero-Int = 32,000 kms, rather like the measure of the electron density by the thermal noise radio experiment on ICE, the FWHM we measure is much wider (12,000 km) than seen by this ICE experiment.

Our P/Halley data rate is, as expected, far outracing my small group's ability to handle the 2-D spectrophotometric digital data. But we do have some really good stats on:

- (i) Self-consistent oxygen and thence  $H_2O$  production rates for the comet from 2.9 A.U. into about 1.3 A.U. heliocentric distance. The strong  $NH_2$  bands have proven an annoyance; they blend with the  $6300\text{\AA}$  [OI] line more fiercely in the Hally spectra than in any other comet I have observed before. P/Halley's derived  $Q(H_2O)$  ranged from about  $2 \times 10^{27}$  mols $^{-1}$  at  $r = 2.9$  A.U. to  $> 6 \times 10^{28}$  at  $r = 1.35$ .
- (ii) A study of the onset of the ion tail through careful picture-processing of the  $H_2O^+$  ionic lines, especially their non-symmetric distribution along the sun-comet nucleus-tail radius vector. We have now also imaged the inner coma tail rays in  $H_2O^+$  on two occasions and intend to make a quantitative study of them. Is there any ionized matter between these rays?
- (iii) We have searched for new, weak molecular emissions, especially those with short scales (potential parent molecules). To date,

we have detected several interesting looking but rather weak molecular emissions that are very concentrated to the cometary nucleus. They are all in the near IR; the best being near 7075 and 7380 Å. They are slightly more concentrated to the nucleus than the previously known short scale photoionized species [OI] and NH<sub>2</sub>. I have just started this research with student Patrick McCarthy, so an identification is still a ways off. I will be continuing this work through calendar year 1986, at least (if the Southern Hemisphere data are as good as we hope).

- (iv) On blue-region two-D spectra of P/Halley's inner tail, we have located the ions due to CO<sub>2</sub><sup>+</sup>, OH<sup>+</sup>, CH<sup>+</sup> and (weakly) CO<sup>+</sup>. The comparison of OH<sup>+</sup> and CO<sub>2</sub><sup>+</sup> in P/Halley and any future comets with even weak ion tails should provide invaluable data on the CO<sub>2</sub>/H<sub>2</sub>O ratio near the nucleus.

c. Proposed Research

In the next months we will continue the above observational attack on P/Halley through imaging and spectroscopy. One new wrinkle, hopefully to be tried in Chile and Australia, is to look for the neutral water overtone and combination band in resonance fluorescence near λ7225. This may be possible, from the ground, with a dry site and a favorable geocentric Doppler shift. If successful, such an observation would yield the spatial emission profile of the main parent molecule.

d. Publications

Observations of the Red Auroral Oxygen Lines in Nine Comets, Publ. A.S.P. 94, 1008, 1982.

Spectrophotometry of 17 Comets. I. The Emission Features (with R.L. Newburn), A.J. 89, 289, 1984.

The Detection of the 5577.3 Å Line of [OI] in Comets (with K.S. Krishna Swamy), Earth, Moon, and Planets 30, 105, 1984.

Surface Photometry of Comet Encke (with S. Djorgovski), A.J. 90, 869, 1985.

Kitt Peak Spectroscopy of P/Halley; October 1983-March 1985 (with M. Belton, P. Wehinger, and S. Wyckoff), Uppsala Colloquium on Comets, Asteroids, and Meteorites, 1986. Eds. C.-I. Lagerkvist, et al, p. 491.

Picture Processing of Weak Ion-Tail Emission of H<sub>2</sub>O<sup>+</sup> in Comets P/Crommelin and IRAS-Araki-Alcock (with M.A. Strauss), Uppsala Colloquium on Comets, Asteroids, and Meteorites, 1986. Eds. C.-I. Lagerkvist, et al, p. 443.

Spectrophotometry of Seventeen Comets II. The Continuum (with R.L. Newburn), A.J. 90, 2591, 1985.

Optical Spectrophotometry of Comet P/Giacobini-Zinner and Emission Profiles of H<sub>2</sub>O<sup>+</sup>, Geophysical Research Letters (with M.A. Strauss and P.J. McCarthy), 1986 (in press). Preprint attached.

A SEARCH FOR EARTH-APPROACHING ASTEROIDS

Principal Investigator: L. G. Taff  
 Lincoln Laboratory  
 Massachusetts Institute of Technology  
 Lexington, MA 02173

Co-Investigators: none

The principal objective of this research was to develop new, automated methods for the detection and discrimination of Earth-approaching asteroids. Specifically, utilizing state-of-the-art, electron-bombarded, silicon-diode, beam-scanned, low-light-level television cameras and the most advanced video processing equipment available we aimed to improve the limiting magnitude for a 50% probability of detection, increase the areal search rate, and minimize the burden on humans of the search effort. To this end three increasingly automated and sophisticated versions of the data acquisition, storage, and processing systems have been designed and implemented over the years of this grant.

The secondary objective of this research was to actually search the celestial sphere for Earth-approaching minor planets. This too has been done, at every clear non-Summer lunation, over the last six years. An example of this effort is the recent cataloging of 1982 HS=3343 VNEDZEL. This particular high eccentricity, high inclination object is of a type even more rare than are Earth-approaching asteroids. Several of these have been found by us.

The principal accomplishments of this effort were the fulfillments of our primary and secondary objectives. The current search optimizes telescope time and all detection/discrimination processing is fully automated. Moreover, owing to increased storage, it is performed in the daytime.

## Publications

- Taff, L. G.; A New Asteriod Observation and Search Technique, Publ. Astron. Soc. Pac. 95, 608, 1981.
- Taff, L. G.; Observations of Asteriods, Minor Planet Circulars, assorted.
- Taff, L. G.; Optimal Searches for Asteriods, Icarus 57, 259, 1984.
- Taff, L. G.; On Initial Orbit Determination, Astron. J. 89, 1426, 1984.
- Taff, L. G.; How Many Earth-Approaching Asteroids Are There?, in Asteroids, Comets, Meteors II, pg. 31, 1986.

C-3

POLE ORIENTATION, SIDEREAL PERIOD, AND SENSE OF ROTATION OF ASTEROIDS

Principal Investigator: Ronald C. Taylor  
 Space Sciences Building  
 University of Arizona  
 Tucson, AZ 85721

Co-Investigators: Tom Gehrels

We propose to use photometric astrometry, a method that uses precise lightcurve epochs, in order to derive the pole orientation, sidereal period, and sense of rotation of asteroids for which there now exists an adequate data base.

We propose to use photometric astrometry to derive the pole orientation of the planet Pluto. The method will be independent of any recent theories or conclusions that have been based on the Pluto-Charon system.

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Over the past 18 years Taylor has been actively involved in the determination of pole orientations of asteroids. The method, called photometric astrometry, takes precise epochs of lightcurves into account.

We will be involved in pole determination research on asteroids 532 Herculina, 45 Eugenia, and 3 Juno. Also, there is a cooperation with P. Magnusson of Sweden in analyzing discrepancies between various pole determination techniques presently being used.

Taylor is a participant in a group actively involved in both the study of asteroid shapes and in creating a generalized "master" pole determination technique which will incorporate the best features of several current methods (some from the United States are A. Harris, J. Ostro, E. Bowell, J. Drummond and E. Tedesco along with some from Europe such as J. Surdej, V. Zappala, and P. Magnusson). The larger group plans to meet at the DPS meeting next Fall in Paris.

Aside from research and publication collaboration with astronomers in Europe and Australia, Taylor and Jean Surdej of Belgium are submitting a proposal for Space Telescope time in order to study both the pole orientations of asteroids and to search for binary asteroids.

Since NASA announced the "Comet-Rendezvous-Asteroid-Flyby" in the summer of 1985, Taylor has organized two dozen lightcurve observers from around the globe into a cooperative group ready to gather groundbased data of potential targets. The lead time between the target announcement and the actual rendezvous should be sufficient to enable determination of pole orientation of the target.

#### Recent Publications Relevant to this Work

- "Pole Orientation of 16 Psyche by Two Independent Methods," E. F. Tedesco and R. C. Taylor, Icarus 61, 241-251, 1985.
- "The Pole Orientation of Asteroid 433 Eros Determined by Photometric Astrometry," R. C. Taylor, Icarus, 61, 490-496, 1985.
- "The Rotation Period and Pole Orientation of Asteroid 4 Vesta," R. C. Taylor, S. Tapia, and E. F. Tedesco, Icarus 62, 298-304, 1985.
- "Photometric Lightcurves of 21 Asteroids," C. D. Vesely and R. C. Taylor, Icarus 64, 37-52, 1985.
- "Asteroid 532 Herculina: Lightcurves, Pole Orientation, and a Model for its Shape," R. C. Taylor, P. V. Birch, J. Drummond, A. Surdej, and J. Surdej, Icarus, in preparation.

## ASTEROID SHAPES AND POLE ORIENTATIONS FROM VISUAL AND INFRARED PHOTOMETRY

Principal Investigator: Edward F. Tedesco  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: none

### a. Objectives:

1. To determine the spin rates, shapes, and pole orientations of selected asteroids. Data of this kind are fundamental in that they provide important constraints on theoretical models of asteroid collisional evolution, impact cratering effects, material strengths, and regolith development.
2. To derive the best possible values obtainable from remote observations on the sizes, shapes, and densities of Pluto and its satellite Charon and to obtain an albedo map of one hemisphere of Pluto. Accurate densities will enable meaningful constraints to be placed on possible bulk compositions.

### b. Accomplishments:

1. Determined the shape and pole orientation of asteroid 16 Psyche (Tedesco and Taylor, 1985).
2. Presented new evidence supporting the shorter, five hour, period for 4 Vesta (Taylor, Tapia, and Tedesco, 1985).
3. Detected the first "mutual eclipse" event between Pluto and Charon (Binzel et al., 1985).
4. Began the organization of an international campaign to obtain lightcurves and other data on the Pluto-Charon mutual events. Conducted a "Pluto Workshop" at the 1985 meeting of the Division for Planetary Sciences.



c. Proposed Research:

Because of the time-critical nature of the Pluto-Charon mutual eclipse events this task will concentrate on obtaining and analyzing observations of Pluto-Charon mutual events during the entire eclipse "season", i.e., over the next five or six years, in order to extract the maximum information possible from this once per 125 year opportunity. Due to the transient nature of these events the chances for success are maximized by a cooperative effort among several observatories. Indeed, such a cooperative effort had already been organized and at the time the first events were detected in early 1985 included the McDonald Observatory (R. Binzel), the University of Arizona Observatories (R. Marcialis), Palomar Observatory (E. Tedesco et al.), and the Mauna Kea Observatory (D. Tholen). Following the detection of the first mutual events came the ability to accurately predict future events. Hence, beginning in September 1985 a campaign to obtain worldwide coverage of these events was organized and to date 92 astronomers from 23 different countries have expressed an interest in participating.

Telescope time under this project (on the Kitt Peak 50-inch, the Palomar 60-inch, and the Table Mountain 24-inch telescopes) has already been obtained for the 1986 events.

d. Publications:

Binzel, R.P., Tholen, D.J., Tedesco, E.F., Buratti, B.J., and Nelson, R.M. (1985). The detection of eclipses in the Pluto-Charon System. *Science* **228**, 1193-1195.

Taylor, R. and Tedesco, E. (1983). Pole orientation of asteroid 44 Nysa via photometric astronomy, including a discussion of the method's application and its limitations. *Icarus* **54**, 13-22.

Taylor, R.C., Tapia, S., and Tedesco, E.F. (1985). The rotation period and pole orientation of asteroid 4 Vesta. *Icarus* **62**, 298-304.

Tedesco, E. T. and Sather, R. E. (1981). Minor planets and related objects XXIX. Asteroid 29 Amphitrite. *Astron. J.* **86**, 1553-1558.

Tedesco, E.F. and Taylor, R.C. (1985). Pole orientation of 16 Psyche by two independent methods. *Icarus* **61**, 241-251.

Tedesco, E. F., Taylor, R. C., Drummond, J., Harwood, D., Nickoloff, I., Scaltriti, F., Schober, H., and Zappala, V. (1983). Worldwide photometry and lightcurve observations of 1 Ceres during the 1975-1976 apparition. *Icarus* **54**, 23-29.

Tedesco, E. F., Taylor, R. C., Drummond, J., Harwood, D., Nickoloff, I., Scaltriti, F., and Zappala, V. (1983). Worldwide photometry and lightcurve observations of 16 Psyche during the 1975-1976 apparition. *Icarus* **54**, 30-37.

PHYSICAL PROPERTIES OF ASTEROIDS

Principal Investigator: Glenn J. Veeder  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: none

a. Objectives:

The study of the physical properties of asteroids by telescopic observations and laboratory and theoretical work. Spectrophotometry from 0.3 to 1.1 microns and 1.2, 1.6 and 2.2 micron photometry allow spectral-compositional classification of asteroids. Based on laboratory data and telescopic observations, we find that infrared measurements at 1.2, 1.6 and 2.2 microns provide a relatively rapid and accurate method for the classification of minor planets and are important in comparing asteroids with meteorites. We have proven this technique during the past years and will employ it in an expanded survey of Apollo-Amor-Aten and other unusual asteroids recently scanned by IRAS.

b. Accomplishments:

During the past year we have obtained JHKN and or Q photometry on 57 asteroids at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea. Among these were 5 planet-crossing objects including the new Aten 1986 EB. We have also applied the standard asteroid thermal model to our 10 and 20 micron measurements of the nucleus of P/Arend-Rigaux and Deimos.

c. Proposed Research:

We will continue 1.2, 1.6, 2.2, 10 and 20 micron survey photometry of planet-crossing asteroids; obtain follow-up photometry of selected unusual objects at additional wavelengths as needed (i.e. CVF of multi-channel spectrophotometry); pursue intensive infrared observations, including lightcurves, of any bright newly discovered Apollo-Amor-Aten asteroids; compare reflectance data from 1.2 to 2.2 microns for asteroids and meteorites in order to examine whether a metallic phase is possible on the surfaces of class S or A asteroids; refine the thermal model for small rocky asteroids by comparison with related objects such as comet nuclei and Deimos.

d. Publications:

Lebofsky, L.A., Sykes, M.V., Nolt, I.G., Radostitz, J.V., Veeder, G.J., Matson, D.L., Ade, P.A.R., Griffin, M.J., Gear, W.K. and Robson, E.I. (1985). Submillimeter observations of the asteroid 10 Hygiea. Icarus 63, 192-200.

Vilas, F., Tholen, D.L., Lebofsky, L.A., Campins, H., Veeder, G.J., Binzel, R.P. and Tokunaga, A.T. (1985). Physical parameters of near-Earth asteroid 1982 DV. *Icarus*, 63, 201-205.

Veeder, G.J., Hanner, M. and Tholen, D.J. (1986). The nucleus of comet P/Arend-Rigaux. *Astron. J.*, submitted.

PASSIVE MICROWAVE REMOTE SENSING OF THE ASTEROIDS  
USING THE VLA: CONTINUATION

Principal Investigator: William J. Webster, Jr.  
 Geophysics Branch  
 NASA/Godddard Space Flight Center  
 Greenbelt, MD 20771

Co-Investigators: none

Objective

We are inferring the structure and composition parameters for a selected set of the main belt asteroids by employing microwave remote sensing techniques developed for Earth observations. Precise flux density measurements made with the Very Large Array (VLA) and the 11 m mm-wave antenna of the National Radio Astronomy Observatory are being used to define the microwave continuum spectra of these asteroids. These spectra will be inverted in order to estimate the near-surface bulk properties (radii, roughness, composition) independent of previous optical or infrared spectroscopy.

Accomplishments

The project is being performed in cooperation with the NRL/USNO/NRAO group (Johnston, Seidelmann and Wade, hereafter JSW) and R.W. Hobbs of CTA, Inc. The two groups have collaborated on high resolution maps of the 2 cm emission of 1 Ceres and 4 Vesta. In the case of 1 Ceres, the diameter derived (850 km) is much less than the 1003 km diameter derived from photometry (see Figure 1). The continuum spectrum indicates that the surface composition is the cause of the discrepancy (see below). The radio diameter of 4 Vesta is near to the photometric value of 538 km and is being refined by the 2 cm data.

The continuum spectrum of 1 Ceres is essentially complete as of June 1, 1985. Figure 1 shows the spectrum normalized to 850 km for the diameter. Using an extensive model data base, the statistical inversion technique has derived a surficial layer of dry clay (i.e. no interpolated water) about 4.5 cm deep. The statistical measures of the quality of the identification yield a 90% confidence level for this result. The solid line in Figure 1 corresponds to this model. Since the IR observers have identified montmorillonite from IR spectroscopy, this result is not surprising.

We have obtained sufficient data to make at least preliminary interpretations of the six asteroids observed in sufficient detail thus far. In Table 1 we summarize the results.

Proposed Research

In the next three years, we expect to complete the spectra of 2 Pallas, 4 Vesta and 10 Hygeia. With the addition of a new cooled 3.3 mm receiver at the 11 m NRAO antenna at Kitt Peak, we will make observations of 15 Eunomia and 704 Interamnia. A definitive interpretation of these objects will then be made. Based on VLA and 11 m scheduling for the previous proposal, we anticipate that two oppositions (about two years) will be required to complete the data set to the extent that is possible.

### Publication

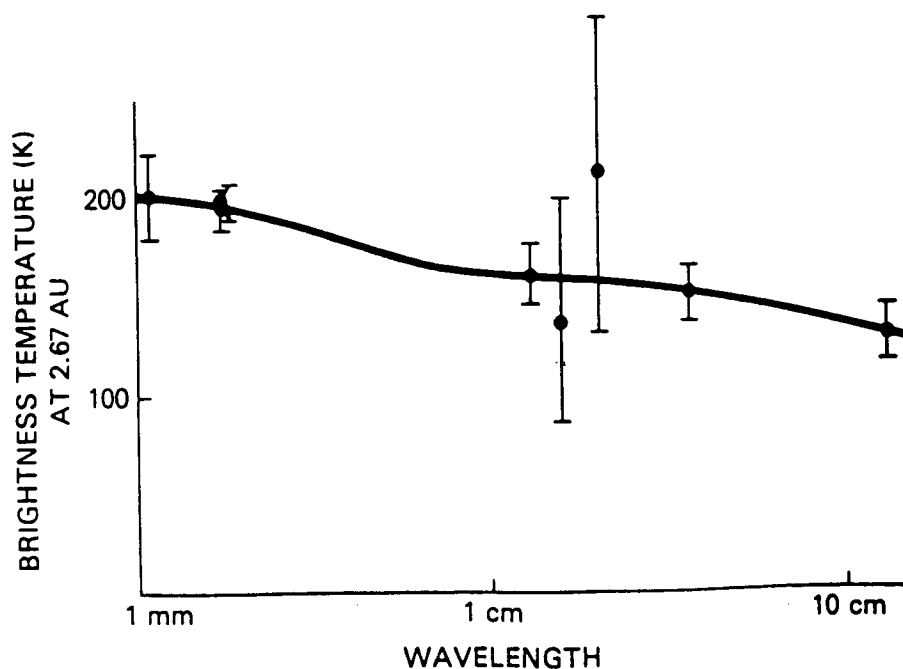
Webster, W.J., Jr., Hobbs, R.W., and P.D. Lowman, Jr., 1984, Detection of  $\lambda=2$  cm Emission from Minor Planet 15 Eunomia, Icarus, 60, 538-540.

Table 1

Inferred Characteristics of Some Major Asteroids

<u>Asteroid</u>	<u>Diameter/Source</u>	<u>Surface Characteristics</u>	<u>Spectral Class</u>
1 Ceres	850 (VLA)	Dry Clay (~4.5 cm) Over "Basalt"	C
2 Pallas	538 (Occultation)	Dust (0.2 cm) Over "Basalt"	U
4 Vesta	555 (Photometric)	Dust (0.5 cm) Over "Basalt"	U
10 Hygeia	443 (Photometric)	Dust (1 cm) Over "Basalt"	C
15 Eunomia	261 (Photometric)	Regolith (1 cm, 10% Voids)	S
704 Interamnia	338 (Photometric)	Deep (>3 cm) Dust	U

### 1 CERES CONTINUUM SPECTRUM (850 km DIAMETER)



ORIGIN OF ASTEROIDS AND SMALL BODIES

Principal Investigator: J.G. Williams  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

Co-Investigators: J. Gibson

**Objectives:** Comets and asteroids are observed with the Palomar 1.5m telescope using a CCD array. The objective is positions and the priorities are comets plus minor planets which are planet crossers, Trojans, Hildas, have high inclinations, or otherwise have unusual orbits. Recoveries of comets and asteroids seen at previous oppositions and follow-up on newly discovered objects are stressed. Surveys and new discoveries are not being attempted. The dark time that we have access to is used for faint objects, while brighter objects can be followed in the more plentiful light time. Since asteroids are usually discovered at perihelion when bright, the next several opportunities for recovery are faint. Thus big telescopes complement astrograph discoveries.

**Accomplishments:** During the past year three periodic comets were recovered. They were Tsuchinshan 2, Whipple, and Daniel. Follow up positions on four newly discovered comets appeared on IAU cards: Machholz, Hartley, Maury, and Shoemaker 3. Halley was captured shortly after its 1985 conjunction and a set of exposures in late summer was one of the earliest showing tail development (those were given to other researchers). A variety of interesting asteroids were also captured.

**Proposed Research:** A CCD observing program will be continued on the 1.5m Palomar telescope for the recovery of faint comets and minor planets. This will emphasize first opposition follow up and second opposition recovery positions. Comets and unusual asteroids will be given priority. This will not be a survey program.

**Publications:** The comet recoveries and other time critical observations were given on IAU cards 4062, 4063, 4078, 4079, 4088, 4090, 4092, 4107, and 4171.

SPECTROSCOPY OF COMETS

Principal Investigator: Susan Wyckoff  
 Peter A. Wehinger  
 Physics Department  
 Arizona State University  
 Tempe, AZ 85287

Co-Investigators: none

**Objectives:** Comets constitute the most accessible samples of the outer solar system in its most primitive state. Our goal is to determine the physical and chemical properties of comet nuclei to infer the conditions and processes related to the origin and evolution of the outer solar system. The procedure is to acquire and analyze digital spectra of a sample of comets covering a large range in heliocentric distance. During 1984-6 the emphasis has been on Comet P/Halley (1982i). Large ground-based telescopes and state-of-the-art detectors have been used to observe Comet P/Halley pre- and post-perihelion, covering a heliocentric distance range, 0.9 to 6.1 AU.

**Accomplishments:**

- First detection of onset of sublimation in a comet and evidence for water ice controlling sublimation in P/Halley.
- First spectroscopic detection of gas coma in P/Halley(1982i).
- Gas and dust production rates of P/Halley,  $r = 6$  to 0.9 AU, indicate  $Q(H_2O) = r^{-4}$ .
- Measured velocities and tailward accelerations of  $H_2O^+$  ions in P/Halley indicate for the first time bulk mass motions, not wave motions in the plasma tail.
- Detection of new molecular species in the spectra of P/Halley.
- Discovery of significant chemical composition differences in the pre- and post-perihelion nucleus in P/Halley.
- Analysis of 1910 objective prism plates of P/Halley obtained at Lowell Observatory by V.M. Slipher reveal unusually weak  $C_3$  relative to  $C_2$  compared to the 1986 apparition.
- Gas and dust production rates, and  $CO^+/H_2O^+$  abundance ratio determined for P/Giacobini-Zinner(1984e) at the time of the ICE encounter.
- Spectroscopic data on 20 faint comets covering  $r = 0.7$  to 3.5 AU obtained.

**Proposed Research:** Digital spectra of P/Halley have been obtained from 1984 to the present using large ground-based telescopes (Kitt Peak, Cerro Tololo, Multiple Mirror, Lowell). Long-slit CCD spectra were obtained at CTIO at the times of the Vega and Giotto encounters with P/Halley. Telescope time(CTIO,AAT) has been allocated to continue our spectroscopic program in April, May and June 1986. A proposal for telescope time to monitor the outbound spectral evolution of the comet has been submitted to CTIO.

From the analysis of the spectroscopic data we expect to:

- Determine pre- and post-perihelion dependence of the gas and dust production rates on heliocentric distance.
- Study long and short timescale variations in the gas, ion and dust production rates.
- Search for new molecular species in the coma and tail.
- Determine the global physical conditions (ionization, excitation, velocities, abundances, etc.) in the coma and ionosphere at the times of the Vega and

Giotto encounters with Comet P/Halley.

- Monitor the post-perihelion turn-off of the coma of P/Halley.
- Map the velocity field in the  $\text{H}_2\text{O}^+$  plasma in P/Halley from a projected distance  $2 \times 10^3$  km sunward to  $2 \times 10^6$  km tailward of the nucleus.
- Map monochromatic intensity profiles of OH,  $\text{OH}^+$ , NH, CN,  $\text{C}_2$ , CH,  $\text{CH}^+$ ,  $\text{C}_3$ ,  $\text{NH}_2$ , [OI],  $\text{CO}^+$ ,  $\text{H}_2\text{O}^+$ , from long-slit CCD spectra to determine scalelengths.
- Compare 1910 data with similar objective prism Schmidt data of P/Halley obtained in March 1986 to study nucleus inhomogeneities on a timescale of the orbital period.
- Continue program to determine spectroscopic characteristics of comets as a function of heliocentric distance for comparison with P/Halley data, and obtain spectroscopic data of P/Schwassmann-Wachmann 1 to study quiescent and outburst states of the nucleus.

#### Publications:

"Onset of Sublimation in Comet P/Halley (1982i)" *Nature*, 316,241, 1985, (with R.M. Wagner, M. Festou and D. Schleicher).

"Detection of CN Emission in Comet P/Halley (1982i)", in *Asteroids, Comets, Meteors II*, eds. C.-I. Lagerkvist, B.A. Lindblad, H. Lundstedt, H. Rickman, p.487, 1986, (with M. Belton).

"Kitt Peak Spectroscopy of P/Halley: October 1983 - March 1985", in *Asteroids, Comets, Meteors II*, eds. C.-I. Lagerkvist, B.A. Lindblad, H. Lundstedt, H. Rickman, p. 491, 1986, (with H. Spinrad and M. Belton).

"Perihelion Spectrophotometry of Comet P/Giacobini-Zinner (1984e)", *Astrophys. J.* (submitted), 1986, (with R.M. Wagner, B. Lutz and D. Lien).

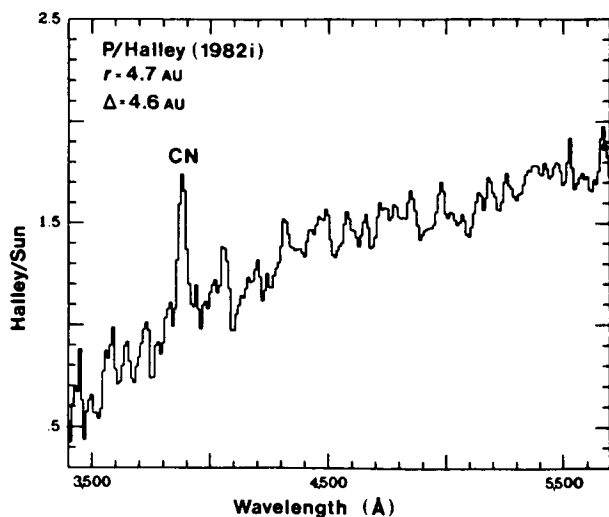


Fig. 1 Detection of the  $\Delta v = 0$  band sequence of the violet CN system ( $B^2\Sigma^+ - X^2\Sigma^+$ ) is illustrated in this averaged (February and March data) pre-perihelion MMT spectrum of P/Halley (1982i) which has been ratioed with the solar spectrum. The CN emission demonstrates the presence of a significant gas coma in the comet. This spectrum was binned in 10-Å intervals before division by the solar spectrum, which was also binned in 10-Å intervals. Note the colour difference,  $\Delta(B - V) \sim +0.2$ , in the sense (P/Halley-Sun) indicated by the slope of the ratioed continua.

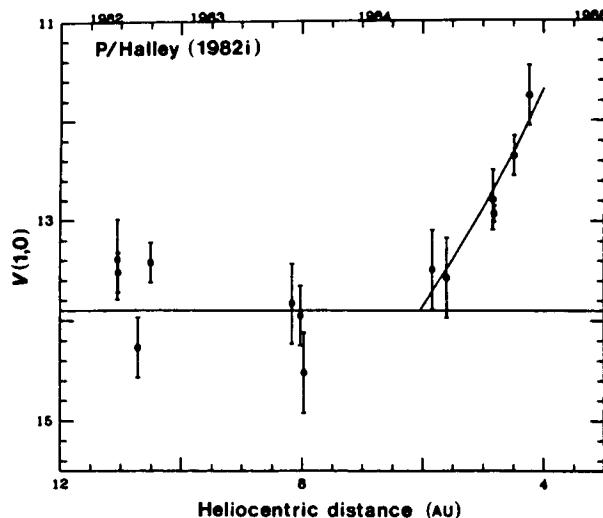


Fig. 2 Evidence for the onset of sublimation of the nucleus of comet P/Halley near  $r \sim 6$  AU.  $V(1,0)$  is the  $V$  magnitude of the comet reduced to a distance 1 AU from the Earth, 1 AU from the Sun and to a direction directly opposite the Sun. An inactive comet nucleus would have a constant  $V(1,0)$  magnitude. Dates at the top represent mid-year epochs.



COMETARY DYNAMICS

Principal Investigator: Donald K. Yeomans  
 Jet Propulsion Laboratory  
 Pasadena, CA 91109

Co-Investigators: none

a. Objectives: In order to provide observers with accurate cometary ephemerides, up-to-date astrometric positions must be used to update the existing orbit and ephemeris for each object. In addition, nongravitational forces must be taken into account; these forces are assumed due to the rocket effect of outgassing cometary ices. Once successfully modeled, the cometary nucleus spin direction, spin axis evolution, and the volatility of the nucleus' ices can be inferred. The predicted ephemerides also become far more accurate.

b. Accomplishments: Using recent astrometric observations of several periodic comets, their nongravitational parameters were modeled and their orbits and ephemerides updated. Using all the available astrometric observations from each apparition, the nongravitational parameters, orbits and ephemerides were computed for the following periodic comets and minor planets;

Object	Observation Interval	Importance
Comet Olbers	1815-1956	Intermediate Period Comet
Comet Pons-Brooks	1812-1954	Intermediate Period Comet
Comet Brorsen-Metcalf	1847-1919	Intermediate Period Comet
Comet Westphal	1852-1913	Intermediate Period Comet
Comet Brooks 2	1889-1980	Nucleus characterization being studied with Z. Sekanina
Comet Wild 2	1978-1984	Target Comet For CRAF Mission
Asteroid 29 Amphitrite	1902-1982	Galileo flyby in Dec. 1986

In addition, accurate ephemerides for approximately 12 comets and asteroids were computed and distributed to observers who required them for their observing programs.

c. Proposed Research: During FY86 and FY87, the orbits and nongravitational parameters will be determined for periodic comets Tempel 1 and Tempel 2, two comets that have recently been identified as future targets for the Mariner Mark II (CRAF) mission and an alternative flyby, sample return mission. In addition, ephemerides and orbits will be determined for other comets and asteroids of interest to observers and flight project personnel.

d. Publications:

Yeomans, D.K., and Brandt, J.C. The Giacobini-Zinner Handbook; An Observer's Guide to the first Comet to be Explored by a Spacecraft JPL 400-254, 1985.

Sekanina, Z., and Yeomans, D.K. Orbital Motion, Nucleus Precession, and Splitting of Periodic Comet Brooks 2, *Astronomical Journal*, v. 90, No. 11, pp. 2335-2352, 1985.

Yeomans, D.K. The Intermediate Period Comets and Nongravitational Effects, *Astronomical Journal*, April, 1986 (in Press).

#### IV. PLANETARY DETECTION PROGRAMS

WORKSHOP ON EARTH-ORBITAL PLANETARY ASTRONOMY

Jay T. Bergstrahl, Jet Propulsion Laboratory  
Michael J.S. Belton, NOAO

During the last 15 years, we have witnessed a revolution in our understanding of the physical nature of the solar system. The most conspicuous contributions have come from investigations on spacecraft, ranging from the early Explorers to the current Voyagers. Less conspicuous but equally important are the discoveries that have come from parallel investigations in ground-based, airborne and Earth-orbital astronomy. The role of Earth-based remote observations in achieving the goals of Solar System Exploration's Planetary Astronomy Program are currently under review. To assess the specific need for future Earth-orbital facilities, a workshop was convened at Jet Propulsion Laboratory on 13-15 January, 1986. The charter of the workshop included requests to (1) identify the need for Earth-orbital observations within the context of the current goals of the Solar System Exploration Program and (2) identify candidate facilities and instruments required to support these needs.

A comprehensive report on their workshop is presently being prepared.

The following set of conclusions were arrived at by general consensus during the workshop, following the presentation of a range of scientific issues, historical experience, and observational opportunities current in Earth-orbital planetary astronomy. Explanatory notes to these statements are given in the report.

- (1) The achievement of the basic goals of Planetary Science will require scientific investigations from earth-orbit that both supplement and complement the existing programs of planetary missions, airborne, and ground-based astronomy.
- (2) There are a number of specific earth-orbital investigations that deserve immediate consideration for programmatic support and which cannot be accomplished using currently authorized Earth-orbital facilities.
- (3) Significant solar system investigations can be done, and are expected to be done, utilizing major astrophysical observatories being developed by the NASA Office of Space Science and Applications (OSSA) under the direction of the Astrophysics Program.
- (4) The requirements of earth-orbital solar system investigations are not being addressed adequately by the line of astrophysical observatories currently being developed by the Astrophysics Program in OSSA.
- (5) In order to achieve the objectives and potential of Earth-Orbital Solar System Astronomy, a program of spacecraft, telescopic and instrumental development is urgently needed to meet the specialized requirements of observing solar system objects from Earth orbit.

- (6) Consideration of a specific budget line should be associated with Space Station projects O SSA's Solar System Exploration Program.

SPECTROSCOPIC PLANETARY DETECTION

Principal Investigator: Drake Deming  
Planetary Systems Branch  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771

Co-Investigators: Fred Espenak, John J. Hillman,  
Theodor Kostjuk, Michael J. Mumma,  
Donald E. Jennings

Objective:

The goal of this investigation is to determine the extent to which planetary companions to solar-type stars can be detected by measuring the small Doppler reflex which their orbital motion induces in the spectrum of their parent star. Several research groups are actively engaged in making such measurements. A possible problem with such a method is that changes in stellar surface convection may produce spurious changes in stellar spectra, which mimic the effect of planetary companions. The report of the most recent NASA Planetary Detection Workshop called for an investigation of the Sun's integrated radial velocity behavior over the long term, so that solar-cycle effects can be identified and their impact on planetary detection efforts can be evaluated. Accordingly, we are measuring the spectrum of the Sun-as-a-star using Fourier transform and laser heterodyne spectroscopy to search for small Doppler shifts related to the solar cycle.

Accomplishments:

We began monitoring the Sun-as-a-star using the McMath Fourier transform spectrometer (FTS) on Kitt Peak in 1983. In 1985 we made our first measurement using the laser heterodyne technique. Our FTS measurements now extend for three years, with errors of order 3 meters/sec at a given epoch. Over this 3 year period, we have measured a 33 meter/sec change in the apparent velocity of integrated sunlight. The sense of the effect is that a greater blueshift is seen near solar minimum, which is consistent with expectations based on considering the changing morphology of solar granular convection. Presuming this effect is solar-cycle-related, it will mimic the Doppler reflex produced by a planetary companion of approximately two Jupiter masses, with an 11 year orbital period. Thus, Jupiter itself is below the threshold for detection by spectroscopic means, without an additional technique for discrimination. However, for planetary companions in shorter period orbits ( $P \sim 3$  years) the threshold for unambiguous detection is well below one Jupiter mass.

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### Proposed Research:

We will continue our measurements of integrated sunlight, in order to determine whether the effect we have observed reverses after solar minimum has passed. If so, it will strongly indicate that the effect is solar-cycle-related. We will then seek to determine what other observable properties of the Sun-as-a-star correlate with the velocity drift. The identification of such correlations will assist the stellar observers in discriminating between the velocity signatures of stellar activity cycles and the true Doppler reflex of planetary companions.

### Publications:

"On the Convective Noise Floor for the Spectroscopic Detection of Low Mass Companions to Solar Type Stars," D. Deming, F. Espenak, D. E. Jennings and J. W. Brault, to appear in the proceedings of a workshop held at George Mason University (October 14-15, 1985) on "The Astrophysics of Brown Dwarfs," eds. Kafatos and Harrington (Cambridge University Press) 1986.

"On the Apparent Velocity of Integrated Sunlight," D. Deming, F. Espenak, D. E. Jennings and J. W. Brault, (1986), submitted to the Astrophysical Journal.

A SURVEY OF NEARBY STARS FOR THE PERTURBATATIVE EFFECTS  
OF EXTRASOLAR PLANETARY SYSTEMS

Principal Investigator: George D. Gatewood  
Office of Research  
University of Pittsburgh  
Pittsburgh, PA 15260

Co-Investigators: John W. Stein

a. Objectives: To develop a new photoelectric astrometric system, the Multichannel Astrometric Photometer (MAP), and use it in a regular observing program designed to detect extrasolar planetary systems.

b. Accomplishments: The 76-cm refractor of the Allegheny Observatory has been fully renovated to make it suitable as the observing instrument for the MAP. The MAP itself has been designed, constructed and tested in actual operation. A data analysis system has been developed and tested.

c. Proposed Research: The major objective is to observe. Routine observations of a number of fields (target stars and reference stars) will be obtained, reduced, and analyzed for parallax, proper motion, and the presence of planetary perturbations.

d. Publications:

Gatewood, G. (1972) "An astrometric study of Barnard's Star," Ph.D. Thesis.

--- and Stein, J.W. (1980) "High precision astrometry," B.A.A.S. 15, 672.

--- and Stein, J.W. (1983) "Parallax estimates using electronic techniques," Proc. I.A.U. Colloquium 76, 75.

--- Goebel, R., and Stein, J.W. (1978) "The Image Trailer," I.A.U. Colloquium #48, "Modern Astrometry" ed. F.V. Prochazka and R.H. Tucker (Pub. of the U. of Vienna Observatory) p.311.

--- Stein, J.W., Di Fatta, C. and Kiewiet de Jonge, J. (1982) "Accuracy/Magnitude relationship of the Multichannel Astrometric Photometer," B.A.A.S. 14, 884.

--- Stein, J.W., Di Fatta, C., Kiewiet de Jonge, J., Prosser, J., and Reiland, T. (1985) "Short interval estimations of trigonometric parallaxes," P.A.S.P., 97, 345.

--- Stein, J.W., Di Fatta, C., Kiewiet de Jonge, J., and  
Breakiron, L. (1985) "A new astrometric system," Transactions of  
the I.A.U. Symposium 109 (in press).



DETERMINATION OF STELLAR RADIAL VELOCITY PRECISION  
ATTAINABLE WITH A COUDE SPECTROGRAPH

Principal Investigator: William D. Heacox  
 Institute for Astronomy  
 University of Hawaii  
 Honolulu, HI 96822

Co-Investigators: none

a. Objectives: To develop an instrument to measure highly accurate radial velocities of stars, in order to detect low-mass stellar and planetary companions.

b. Accomplishments: The University of Hawaii's Institute for Astronomy has assembled nearly all the resources needed to realize the highest radial velocity precision attainable with conventional coude spectrographs.

c. Proposed Research: The following two component instruments will be added to the existing system, and used with the 48" camera of the 2.24 meter telescope's coude spectrograph: An optical fiber spectrograph coupler capable of reducing spectrograph zonal errors, a highly stable photon-counting array detector (a multi-anode microchannel array). The system will then be tested and used in a program of systematic observations of stellar radial velocities.

d. Publications:

Heacox, W.D. (1980) "An optical Fiber Spectrograph Coupler", in Optical and Infrared Telescopes of the 1990's, K.P.N.D., A. Hewitt, ed.

--- (1980) "Very low amplitude radial velocity variations in Delta Scuti stars," in Nonradial and Nonlinear Stellar Pulsations, H.A. Hill and W.A. Dziembowski, eds., Springer-Verlag

--- and K. Serkowski (1980) "The University of Arizona Radial Velocity Spectrometer," in An Assessment of Ground-Based Techniques for Detecting Other Planetary Systems, Vol. II, D.C. Black and W.E. Brunk, eds., NASA Conf. Pub. 2124

STELLAR OBSERVATIONS WITH THE VOYAGER EUV  
OBJECTIVE GRATING SPECTROGRAPH

Principal Investigator: Jay B. Holberg

Co-Investigators: R. S. Polidan, D. C. Barry

During the periods of interplanetary cruise the Voyager ultraviolet spectrometers are used to provide unique and otherwise unobtainable observations in the extreme ultraviolet (EUV, 500-1200) and the far ultraviolet (FUV, 912-1220 Å). These observations include the spectra of hot stellar sources as well as emission from the interplanetary medium. Recent results of note include: 1) Extensive spectrophotometric coverage of a superoutburst of the dwarf nova VW Hydri, which showed a clear 1/2 day delay in the outburst at 1000 Å relative to that observed in the optical and a curious dip in the FUV light curve near maximum light. The Voyager observations were part of a comprehensive and highly successful campaign involving EXOSAT, IUE and ground based observations of this dwarf nova. 2) A comprehensive study of Be star spectra and variability. These results show the critical importance of FUV observations in the study of the effects of stellar rotation in hot stars. 3) The detection of a strong O VI absorption feature in the spectrum of the PG 1159-like object H1504+65. This detection along with the optical identification of weak O IV lines was a key to the interpretation of this object; which is of extremely high (>150,000K) temperature and appears to be a unique example of a stellar atmosphere devoid of H and He. 4) An analysis of an extremely long duration spectrum of the EUV and FUV sky background, which establishes important new upper limits on both continuum and line emission. This result also provided the first detection of interplanetary Lyman γ.

One of our important long term goals is establishing effective collaborative programs for the analysis of Voyager data. Several such programs currently exist which deal with stellar model atmospheres. For example, an extensive set of DA (pure hydrogen) white dwarf model atmospheres has been constructed in collaboration with F. Wesemael (Univ. of Montreal). These models, specifically tailored to Voyager spectral resolution in the Lyman series region, have been successfully applied to both Voyager and IUE white dwarf observations. Efforts to extend such modeling activity to include other types of stellar atmospheres are underway. Collaborative programs involving just a few specific objects have also proved fruitful. In these instances collaborators have been supplied with reduced Voyager spectra. The recent publication of the first analysis of Voyager and IUE results for three hot sdB stars is an example of this type of collaboration. In order to assist potential collaborators in other fields, we have recently completed a catalogue of Voyager astronomical observations covering the period 1979 to 1986, including over 300 objects.

Over the next 12 months we plan to make observations at the rate of 120 targets per year (a significant increase over the pre-Uranus rate of 80 per year). This period should also see completion of work in several areas. A rather unique FUV spectrum of the QSO 3C273 has recently been obtained and is now being analyzed. Analysis is also nearing completion on Voyager and IUE observations of the symbiotic stars AG Peg and RR Tel. An intriguing feature

of these Voyager spectra is the surprisingly strong presence of O VI (1036 Å) emission, indicating the substantial presence of optically thin high temperature gas in these systems. A comparative analysis of the FUV energy distributions of four PG 1159 objects is also expected to be completed during this period. Wide variations in the strengths of the O VI (1036 Å) absorption feature in these objects are of particular note. One important study closely linked to the Uranus encounter observations is the analysis of the spectra and FUV light curve of the Beta Cephei variable  $\gamma$  Peg. This star was the primary atmospheric occultation star at Uranus and a detailed understanding of its photometric behavior is a necessary part of the final reduction of Uranus stellar occultation data.

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- Peters, G. J., and Polidan, R. S., A New Analysis of the Abundance Standards Iota Hercules and Tau Scorpii, in A New Analysis of the Abundance Standards Iota Hercules and Tau Scorpii, (IAU Symposium No. 111), p. 417, 1985.
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THE RADIAL VELOCITY SEARCH FOR EXTRASOLAR PLANETS

Principal Investigator: Robert S. McMillan  
 Lunar and Planetary Laboratory  
 University of Arizona  
 Tucson, AZ 85721

Co-Investigators: Peter H. Smith

We are observing stars with a ground-based instrument designed to measure small changes in the line-of-sight velocities. The purpose of our observations is to detect large planets by the oscillatory reflex motion they induce on the stars they are orbiting.

The instrument is an optical spectrometer for which wavelengths are first calibrated by transmission through a tunable Fabry-Perot etalon interferometer. Changes in the line-of-sight velocities are revealed by changes in the Doppler shift of the absorption-line spectra of stars.

The scrambling of incident light by an optical fiber and the stability of wavelength calibration by a tilt-tunable Fabry-Perot etalon provide immunity to systematic errors that historically have affected more conventional radial velocity spectrographs. A cross-dispersed echelle spectrograph spatially separates the orders of constructive interference transmitted through the etalon. Selecting several echelle diffraction orders in the vicinity of 4250-4750 Å, which are imaged on a CCD, about 350 points on the profile of the stellar spectrum are sampled by successive orders of interferometric transmission through the etalon. At 4300 Å each interference order is 47 milliangstroms wide and the sample points are 0.64 Å apart, causing distinct, widely-spaced monochromatic images of the entrance aperture to be formed in the focal plane of the camera. Changes in Doppler shift modify the relative intensities of these images, in proportion to the slope of the spectral profile at each point sampled. For simplicity, the data are being analyzed only for changes in radial velocity rather than its absolute magnitude.

With an argon emission line lamp the interferometer is calibrated to better than 2 parts in 100 million; this corresponds to  $\pm 6$  meters/sec in Doppler shift. These calibrations show instrumental variations of  $\pm 12$  meters/sec on a time scale of months; observations of stars are corrected for such changes. The internal repeatability of observations of the differential Doppler shift of Alpha Tau (K5 III;  $B=2.4$ ) is  $\pm 6$  meters/sec for each exposure of 224 square meter-seconds, and  $\pm 8$  m/s for Beta Gem (K0 III,  $B = 2.1$ ). These exposures are obtained in 7 minutes with a 0.91-meter telescope. The external repeatability (day-to-day differential accuracy) of nightly averages of stellar observations is  $\pm 20$  meters/second; improvements to the instrument are planned to reduce this value.

Stars are being observed up to 14 nights every month and data are being reduced. Since September 1985 we have made more than 2000 observations of stars.

Between Dec. 1984 and March 1986 we also have completed other tasks and enhancements, including TV guiding, autocollimator calibration of the interferometer, limited overhaul of the etalon tilt mechanism, reduction in CCD noise, installation of temperature sensors on the interferometer, partial construction of a clean, temperature-controlled, vibration-isolated room for permanent installation of the instrument, and consolidation of instrument controls to allow operation by one person.

During FY 1986 we propose to continue observing, put a new, quieter detector into operation, finish the clean room, and publish our first scientific results.

Current observing programs include a study of small changes in the radial velocity of Arcturus (K1 IIb;  $B=1.19$ ) and other red giant stars on time scales of minutes to months, and radial velocity curves of bright, G-type, short period, single-lined spectroscopic binaries.

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McMillan, R. S., Smith, P. H., Frecker, J. E., Merline, W. J., and Perry, M. L. 1985 in Proc. of IAU Colloq. No. 88, Stellar Radial Velocities, A. G. Davis Philip and D. W. Latham, eds. (Schenectady: L. Davis Press), pp 63-86. The LPL radial accelerometer.

McMillan, R. S., Smith, P. H., Frecker, J. E., Merline, W. J., and Perry, M. L. 1986, in Proc. S. P. I. E. 627, "Instrumentation in Astronomy - VI", ed. D. L. Crawford, in press. A Fabry-Perot interferometer for accurate measurement of temporal changes in stellar Doppler shift.

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JETS, MASS OUTFLOWS AND DISKS ASSOCIATED WITH YOUNG STELLAR OBJECTS

Principal Investigator: Stephen E. Strom  
 Five College Astronomy Department  
 University of Massachusetts  
 Amherst, MA 01003

Co-Investigators: none

a) Objectives: This program is aimed at establishing

- the frequency with which disks accompanying the formation of stars.
- the evolutionary state of these disks (pre-or post- planet building)
- the relationship between disks and mass outflows emanating from young stars (do disks collimate and/or drive the outflows?)
- the relationship between disks, mass outflows and the global properties of molecular clouds.

b) Accomplishments

i) OPTICAL STUDIES OF MASS OUTFLOWS

Over the past 3 years, we have obtained a series of deep CCD images of regions surrounding young stellar objects (YSO's) located in a variety of environments with the goal of providing a census of the properties of mass outflows associated these objects. In late fall, 1985, we completed and submitted for publication in the Astrophysical Journal Supplement Series a catalog describing the optical morphology and kinematics of 38 mass outflows associated with young stellar objects (YSOs). Several important conclusions can be drawn from this observational study:

1. In most cases, mass outflows from YSOs, as traced by optical emission from ionized gas, are highly collimated (opening angles for the outflows are typically  $< 10^\circ$ ); in many cases the phrase "stellar" jet seems an apt description of these narrow, collimated streams of length  $10^3$  to  $10^5$  yr. astronomical units.
2. In some cases, the observed morphology and kinematics suggest that these jets may precess, with characteristic periods of tens to hundreds of years.
3. The orientation of stellar jets is related to the orientation of the magnetic field threading the host molecular cloud for the YSO; in over 70 percent of the cases, the flow and field direction are aligned to within  $25^\circ$ .

4. In two cases (HL Tau and L1551/IRS5; see below), high spatial resolution near infrared observations have revealed an extended, disk-like structure associated with the outflow source. In each case, the disk and outflow axes are aligned.
5. Combined with result (3), this observation suggests that the rotation axes of protostellar objects tend to align with the molecular cloud magnetic field, and that the magnetic field has played an important role in determining the early angular momentum evolution of protostars.

#### ii. DIRECT DETECTION OF DISKS ASSOCIATED WITH YSOs

During the past year, we reported the direct detection of disks surrounding HL Tau and L1551/IRS 5 -- both sources of optical jets and larger-scale mass outflows. In each case, the disk dimensions are on the order of several hundred astronomical units and the disk dust masses approximately  $10^{-7}$  solar masses. The average particle densities in these disks are insufficient to collimate an initially isotropic outflow, but might confine expanding streams which leave the stellar surface already fairly well collimated. Hence, disks may not play a decisive role in outflow collimation; instead, it seems most likely that optical outflows are collimated within a few stellar radii of the YSO surface.

#### iii. INDIRECT DETECTION OF CIRCUMSTELLAR DISKS ASSOCIATED WITH YSOs

We have also embarked on a program aimed at indirect detection of circumstellar disks associated with YSOs. Our technique involves comparison of an observed bolometric luminosity ( $L(\text{bol})$ ) with an independent measure of the "true" luminosity ( $L(\text{spec})$ ) of a YSO which derives from the observed strengths of surface-gravity-sensitive spectral features. Suppose that all YSOs are surrounded by circumstellar disks which intercept a fractional solid angle,  $F$ . These disks are presumed to contain grains which absorb optical photons; "reprocessed", absorbed optical photons appear as IR quanta. For a YSO-disk system viewed pole on

$$L(\text{bol}) \approx (1 + F) \cdot L(\text{spec})$$

while for a system viewed equator-on

$$L(\text{bol}) \approx F \cdot L(\text{spec})$$

We obtained  $L(\text{bol})$  and  $L(\text{spec})$  values for a sample of 60 T Tauri stars later than type K7 and found 5 cases in which

$$L(\text{bol}) < 0.03 L(\text{spec}).$$

We presume that these objects are YSOs surrounded by disks viewed nearly equator-on. This conclusion is significantly strengthened by polarimetric observations of the sample of 60 T Tauri stars. The five stars showing unusually small  $L(\text{bol})$  values are characterized by optical polarization position angles which are themselves unusual: their position angles lie nearly perpendicular to the direction of the

magnetic field threading their parent molecular clouds. Stars such as HL Tau and L1551/IRS 5 which show resolved, edge-on disks show identical polarization characteristics. Our results suggest that the formation of disks is a common if not ubiquitous outcome of the formation of low mass stars and that these disks can be detected in objects of ages  $10^5$  to  $10^{6.5}$  years.

c. Proposed Research

During the next two years, we expect to concentrate our efforts in the following areas:

1. establishing the relationship between outflow, disk axis and magnetic field directions. We plan a major observational effort to establish the magnetic field geometry of the host clouds for outflow sources. For large cloud complexes (e.g. Taurus, L1641), we plan to obtain optical polarization measurements (in collaboration with F. J. Vrba of the USNO) of several hundred stars located within or behind these complexes. Disk orientations and characteristics will derive from our observations. We expect to include in excess of 30 outflow sources in this analysis -- a number we believe should be sufficient to ascertain with certainty the relationship between the magnetic field, disk and outflow properties.
2. establishing the ubiquity and characteristics of circumstellar disks associated with YSOs of differing mass. This effort will involve both high spatial resolution near-infrared and polarimetric observations of a large sample of YSOs. Our early efforts will concentrate on the late-type T Tauri stars identified as disk candidates from L(bol) and L(spec) and polarimetric observations. We will later expand our survey to include objects of higher masses.
3. establishing the gas/dust ratio in several of these disks in order to determine the evolutionary state of the disk (pre- or post-planet-building). Here we expect to make spectroscopic observations of molecular carbon and mm-interferometric studies of CO (in collaboration with Anneila Sargent) for a number of YSOs surrounded by disks
4. understanding the location of outflow collimation. Here we plan to concentrate our efforts on studies of stars associated with cometary nebulae. Spectroscopic observations of scattered light along the axes of these nebulae should permit us to establish the latitude dependence of outflow velocity and rate from observations of lines formed at a variety of distances (a few stellar radii to a few au) from the surface of the star.
5. establishing the relationship between optical and molecular outflows. Do they have the same origin? Is the momentum and energy of the molecular flow consistent with that inferred for the stellar jets? Here we plan to combine mm-line studies with optical spectroscopic studies of optical outflow regions in order to chart the relationship between these two manifestations of YSO outflows.



d. Publications

Narrow-band Imaging and Velocity Maps of Young Stellar Objects:  
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S. Wolff and K. M. Strom.

High Spatial Resolution IR Observations of Young Stellar Objects: A  
Possible Disk Surrounding HL Tau, 1984, Ap. J. Lett. 283, L57 -  
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M. Matthews; U. of Arizona Press), p. 17.

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J. Letters, 297, L41, with R. Mundt, J. Stocke, and K. M. Strom.

An Optical and Infrared Study of the Region Surrounding Herbig-Haro  
Objects 1 and 2, 1985, A. J., 90, 2281, - with K. M. Strom, G. L.  
Grasdalen, K. Sellgren, S. Wolff, J. Morgan, J. Stocke and R.  
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J. 290, 587 - with R. L. Snell, J. Bally, and K. M. Strom.

A Study of the Morphology and Kinematics of the Dense Gas Associated  
with Star Forming Regions, 1986 Ap. J. (in press), (with M. H.  
Heyer, R. L. Snell, P. F. Goldsmith and K. M. Strom)

Optical Manifestation of Mass Outflows from Young Stars: An Atlas of  
CCD Images of Objects, 1986, Ap. J. Supple. (in press) with K. M.  
Strom, S. C. Wolff, J. Morgan and M. Wenz.

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Molecular Outflow Regions, 1986, A. J. (submitted) with F. J.  
Vrba, K. M. Strom, M. H. Heyer.

Extended Far-Infrared Emission Associated with Mass Outflows from  
Young Stars I. L1551, IRS 5, 1986, Ap. J. (Letters) submitted with  
S. Edwards, R. L. Snell, T. H. Jarrett, C. A. Beichmann, K. M.  
Strom.

Mass Outflows Associated with Young Stellar Objects, invited review  
presented at IAU Symposium 115 "Star Forming Regions", Tokyo,  
Japan, S. E. Strom, K.M. Strom.

PLANETARY OPTICAL AND INFRARED IMAGING

Principal Investigator: Richard J. Terrile  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

Co-Investigators: Bradford A. Smith

Objectives: The purpose of this investigation is to obtain and analyze high spatial resolution CCD coronagraphic images of extra-solar planetary systems and infrared images of the outer planets. These data will provide information on the distribution of planetary and proto-planetary material around the nearby stars leading to a better understanding of the origin and evolution of planetary systems. Imaging within our solar system will provide information on the current cloud configurations on the outer planets, search for new objects around Uranus and Neptune, provide atmospheric rotation periods in support of Voyager, and search for material around asteroids in support of the Galileo project. Infrared imaging of Jupiter will also provide continuity between the Voyager and Galileo projects.

Accomplishments: Over the last year this program acquired images of a circumstellar disk of orbiting material around the nearby star  $\beta$  Pictoris. This material is believed to be associated with the formation of planets and provides a first look at a planetary system much younger than our own. Preliminary work was also done to acquire multi-color photometric data and polarimetry on the  $\beta$  Pictoris disk as well. A coronagraphic search for other proto-planetary systems is also underway. Coronagraphic imaging provided the first clear images and a determination of the geometric albedo of the rings of Uranus. A search for material around the asteroid Amphitrite showed that the region around the asteroid was free of particles larger than 500 meters in radius or diffuse material with an optical depth larger than  $10^{-6}$ . NASA IRTF infrared images of Jupiter and Saturn are providing information on the relative heights and cloud top temperatures of atmospheric features.

Proposed Research: A survey of the nearby stars will be continued in order to provide information on the probability of circumstellar material around stars as a function of spectral class and to understand the morphology of young planetary systems. Further imaging of the Beta Pictoris system will also be done in order to obtain spectro-photometric and polarization data on the disk and to image the disk with smaller occulting masks to understand the distribution of material close to the central star. Coronagraphic imaging of Uranus and Neptune will continue in order to refine the atmospheric rotation period of Neptune and to spectroscopically image the ring systems of the outer planets. Infrared imaging of Jupiter and Saturn will also be used to continue an analysis of the atmospheric structure and to support the Galileo project by continued monitoring of the Jovian cloud heights.

Publications:

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V. INSTRUMENT DEVELOPMENT

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LINEAR ARRAY CAMERA  
MODIFICATION AND SUPPORT FOR USE AT GROUND BASED OBSERVATORIES

Principal Investigator: R.H. Brown  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

- (a) Add a multi-position filter wheel to the JPL Linear Array Camera and to provide support for planetary observations at ground based observatories with the modified camera.
- (b) This is a new task
- (c) This year a filter wheel will be constructed, installed and tested, and the instrument will be used for as many as 7 observing runs, 3 of which will be of Halley's Comet carried out at Mauna Kea Observatory in Hawaii. The design of the filter wheel has already been completed and construction and installation only await funding. The observations of Comet Halley will be made in the 1.2-5 $\mu$ m region to study the evolution and dynamics of Halley's coma as it approaches and recedes from the sun in 1985 and 1986.
- (d) Not Applicable

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## MICROWAVE RADIOMETER DEVELOPMENT

Principal Investigator: M. A. Frerking  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

Co-Investigators: none

This task supports instrumentation development. The primary responsibility is the design and fabrication of state-of-the-art submillimeter receivers to be used for spectroscopic observations of planetary atmospheres, interstellar clouds, and comets. Elements of this work are done in collaboration with other submillimeter tasks as JPL and Caltech.

The dual frequency (183 and 380 GHz) cooled-mixer radiometer was improved, installed, and successfully flown on the Kuiper Airborne Observatory during the expedition to New Zealand to observe Halley's comet. During the observations, two new interstellar sources of water were discovered. Both the klystron local oscillator at 183 GHz and the carcinotron local oscillator at 380 GHz were replaced with solid state Gunn oscillator driven multipliers. A new 256 channel filter bank with 1 MHz resolution was integrated in the receiver. The system performance in the field was extremely good, equaling state-of-the-art performance of GaAs Schott diode receivers in the laboratory. The noise temperature of the 380 GHz system was 680 K DSB over a 256 MHz IF bandwidth, while that of the 183 GHz system was 390 K DSB.

Funding from this task will be used for critical engineering (0.5 WY) for the design and fabrication of the quasi-optical components to mount the 650 GHz radiometer on the 10 meter Caltech submillimeter antenna on Mauna Kea.

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## **VI. LABORATORY STUDIES**

INTERPLANETARY AND INTERSTELLAR DUST

NRC Research Associate: Scott Sandford  
NASA/Ames Research Center  
Moffett Field, CA 94035

Objectives:

Our primary objective is to establish whether polycyclic aromatic hydrocarbons (PAHs) are present in the interstellar medium, and if so, what spectral features they can explain. Since these molecules are relatively tough, we intend to explore the possibility that interstellar PAHs survived the formation of the solar system and became incorporated into comets and asteroids. If this is the case, then we would expect to find traces of PAH-like material in the collected IDPs and in meteorites. The presence of PAHs in extraterrestrial materials is suggested by several observations. PAH-like molecules have been found to be a major component of meteorite acid residues. Also, Raman spectra of IDPs show absorption bands and fluorescence features that are similar to that expected from PAHs. Finally, the D/H enrichments seen in many IDPs and meteorite acid residues can be explained in terms of photoprocessing of PAHs in the interstellar medium.

In addition to the joint work being done with Lou Allamandola, I am also working independently on a method that uses solar flare track densities measured in IDPs to determine whether the major sources of the IDPs are asteroids or comets.

Accomplishments:

We have produced several processed PAH samples to date. The Raman spectra and D/H ratios of these samples will be studied in the near future.

A manuscript has been sent to Icarus which gives a detailed discussion of the possibility of using solar flare tracks in IDPs to determine a cometary vs. asteroidal source of the IDPs. The technique looks promising and a program has been started to measure the large number of IDP track densities necessary to address the issue of the source(s) of the dust. The results could potentially tell us a great deal about comets and/or asteroids.

Proposed Research:

We intend to obtain ultraviolet, visible, and infrared spectra of processed PAHs and ices and compare them to spectra taken from astrophysical objects. We also plan to look for D/H enrichments in the PAH residues and compare them to the enrichments seen in IDP and meteorite samples. Finally, we intend to look at noble gas trapping in processed PAHs and investigate the possibility that PAH-like materials are responsible for the efficient trapping of noble gases that is seen in meteorite acid residues.



Publications:

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A RESEARCH PROPOSAL ON SPECTROSCOPY OF GASES AND SOLIDS  
OBSERVED IN THE SOLAR SYSTEM

Principal Investigator: Francisco P. J. Valero  
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Space Science Division  
NASA-Ames Research Center  
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Co-Investigators: Louis J. Allamandola, Charles Chackerian, Jr.,  
Lawrence P. Giver, David Goorvitch

It is well recognized and accepted that the interpretation and analysis of any type of remote planetary spectroscopic observation requires that basic molecular parameters be available. Furthermore, the newly developed capabilities of air, ground, and space borne spectrometers trained on bodies in the solar system are producing results which are extremely difficult to understand on the basis of available data. This is particularly true in the case of spectral features arising from gases and volatiles condensed as ices.

With the objective to continue to extend our understanding of spectroscopic observations of solar system objects (including comets) we propose laboratory studies of both gas phase molecules and ices and dusts.

In general terms our proposed research plans, that cover three years, are as follows:

- a.) Trace Element Hydrides. The first step will be to build the 1 meter cryogenic BOMEM-compatible White absorption cell. Next we will proceed to obtain the laboratory data using the ultra-high resolution BOMEM Interferometer. Our direct retrieval computer code (Chackerian and Guelachvili, 1983, and Gasster, et al. 1985) will be used for the data analysis.
- b.) Hydrocarbons. The cryogenic cell will also be used for this research together with the BOMEM Interferometer and our retrieval and band modeling computer codes.
- c.) Solar System Ices. Newly developed laboratory facilities will be used for this work. A dedicated low-resolution Fourier Transform interferometer will be procured for this system. In the mean time, the BOMEM Interferometer will be used. Data analysis will be performed utilizing our computer facilities. Comparison and analysis of laboratory and observational data will be done.

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VII. INTERNATIONAL HALLEY WATCH

THE INTERNATIONAL HALLEY WATCH

Principal Investigator: Ray L. Newburn, Jr.  
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California Institute of Technology  
Pasadena, CA 91109

a. Objectives

The International Halley Watch has been designed to maximize the scientific value of ground-based observations of Halley's Comet. Important in their own right, such observations have also enhanced the value of space observations, setting the brief duration flyby data in the context of the overall apparition, placing the extremely high resolution encounter data into the normal scale of observations, and filling in missing data. The IHW has standardized observing techniques wherever useful and possible, coordinated the observing, and is now collecting data for publication in a comprehensive Halley Archive. The IHW has been designed to avoid the problems of 1910 where the two major monographs on Halley were not published until 21 and 24 years later and where much data remains unpublished to this day. The Giacobini-Zinner Watch provided support to the ICE mission and complements the IHW by using the same ground-based techniques at the same time to study another very different comet for comparison.

The IHW has strongly supported the various space missions to P/Halley and P/Giacobini-Zinner, furnishing precision astrometric positions and ephemerides as well as information on dust hazards, photometry, etc. It will continue to help by placing the brief duration, spacecraft flybys into the context of the multi year apparition.

For the IHW to achieve its real potential, the data now must continue to be taken after perihelion and it must all be archived. The best scientific results can be achieved only by having all types of data taken on a given day "side-by-side." This archive must be published and made available to scientists everywhere, and it must have the full digital accuracy of the original data.

U. S. planning for solar system exploration includes a comet rendezvous mission high on the list of future missions. Whatever target comet is selected, planning and execution of such a mission will be much more sure, from instrument design and selection to mission strategy, if at least one comet has already been studied in every way possible from the ground (and from Earth orbit and flyby) throughout an apparition.

b. Accomplishments

The eight observing nets are complete. They include 1000 scientist from 51 countries complemented by 1187 amateurs in 55 countries. The seven original nets all took data during the P/Crommelin trial run, and these have been published in a printed archive. Complete Crommelin data tapes have been delivered to Kiev, Bamberg, and to each discipline specialist center. ICE and the Halley missions were successfully navigated to their targets using astrometric positions and ephemerides supplied by the IHW. A massive observing effort by all nets has been under way for nine months, and data are beginning to flow to the

DS centers. A tremendous interest by the public and the media has been handled successfully.

Current estimates of the actual amount of data acquired are given in Tables I and II.

Table I - Data Acquired Through May 1, 1986

Net	Halley	G-Z
Astrometry	4765 positions	1031 positions
Infrared	2500 (819) obs.*	50 (30) obs.*
Large Scale Phenomena	10,000 (2042) plates*	100 plates*
Near Nucleus Studies	5,500 (5,000) images*	350 (300) plates*
Photometry & Polarimetry	14,000 (10,842) obs.*	1000 obs.*
	12 scans (500-2700 pts. each)	
Radio Studies	2000 obs.	400 obs.
Spectroscopy	15,000 (9605) spectra*#	400 (242) spectra*
Amateur	1200 obs.	500 obs.
	500 plates*	100 plates*
Meteor studies	unknown	N/A

\* Number in parenthesis is actual logged observations  
 Preceding number is estimate of what will come in

# About 75% of this number are multiple "cuts" across two-dimensional spectra

Table II - Estimated Data in Archive

Net	Mbytes	
Astrometry	34 -	35
Infrared	12 -	53
Large Scale Phenomena	8,505 -	17,000
Near Nucleus Studies	1,757 -	2,712
Photometry & Polarimetry	568 -	900
Radio Studies	14 -	42
Spectroscopy & Spectrophotometry	10,000 -	100,000
Amateur	41 -	65
Meteor Studies	1 -	10
	20,932 -	120,817

\* Not including Space Mission data.

c. Proposed Research

Observing of Halley will continue intensely for a few months and at a decreasing level through 1988. The major activity for FY87 will be formatting and archiving of data already acquired. Problems associated with production of the printed archive and the digital archive (CD-ROMs) are being researched at the LC, while the DSs actively seek to draw in data and process them.

d. Publications

Edberg, S. J., ed. IHW Newsletters No. 7 & 8 and Amateur Bulletins Nos. 10-16.

Edberg, S. J. and Levy, D. H. Observe: Comets - The A. L. P. O. Guide to Cometary Studies, Astronomical League, Washington D. C., 1985.

Coco, M. and Edberg, S. J. "Halley's Comet: Capturing a Once-In-A-Lifetime Phenomenon," The Rangefinder, Nov. 1985, p. 16 (also appears in Griffith Observer, Dec. 1985).

Newburn, R. L. and Rahe, J. "Coordinating Work on P/Halley, The International Halley Watch," Asteroids, Comets, Meteors II, p. 473, Uppsala, 1986.

Newburn, R. L. Jr. and Rahe, J. "Status of the International Halley Watch" STIP Symposium on Retrospective Analyses and Future Coordinating Intervals, in press, 1986.

Sekanina, Z. and Aronsson, M. "Archive of Observations of Periodic Comet Crommelin made during its 1983-84 apparition" J. P. L. Publication 86-2, Jet Propulsion Laboratory, Pasadena, 1985.

INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR  
PHOTOMETRY AND POLARIMETRY

Principal Investigator: Michael F. A'Hearn  
Astronomy Program  
University of Maryland  
College Park, MD 20742

Co-Investigators: none

To stimulate photometric and polarimetric observations of comets Halley and Giacobini-Zinner. To advise on techniques, to establish standards for the observations, and to archive the final data.

Sample of Accomplishments in 1985:

1. The last of the 75 sets of standard filters were distributed, including re-allocation of several sets from north to south at the beginning of 1986.
2. Observations of the photometric standard stars from several observatories (Charles University, University of Arizona, Lowell Observatory, Universidad de Chile, and Perth Observatory) were collected and synthesized into a standard system of magnitudes. Some of these observations (Lowell Observatory) were funded by this contract.
3. Transformation equations were derived to yield absolute fluxes in various cometary emission bands and in the continuum. These transformations turned out to vary with the comet's radial velocity for some filters and with the filter's temperature for some filters, and from one set of filters to another. All effects were quantitatively assessed.
4. Non-linearities in the extinction as observed through the OH filter were modelled and techniques for linearizing the extinction were developed.
5. Although not among the official goals of the IHW, NASA Headquarters chose to work through the IHW to develop two CCD camera systems, one for A'Hearn's use and one for use by S. Larson (Discipline Specialist for Near Nucleus Studies Net). Designed by Larson, these systems were completely developed with funding which arrived first in March of 1985 and yet the systems were operating in September to observe Halley. Only capital costs were provided. Design time, testing, and use are not funded through the IHW.
6. We went through two iterations of an archive format and are working on a third.

Publications:

- W. Osborne, P.V. Birch and M.A. Feierberg, 1986, Standard Stars for Comet Photometry, Proceedings of the IAU Symp. 118, New Zealand, December 1985, ed. J. B. Hearnshaw and P. Cottrell (in press).
- M. F. A'Hearn, 1986, Coordinated Programs for Comet Halley, Proceedings of the IAU Symp. 118, New Zealand, December 1985, ed. J.B. Hearnshaw and P. Cottrell (in press).

All results from this program are disseminated primarily through newsletters which we distribute to a mailing list of 192 persons



INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR  
LARGE SCALE PHENOMENA

Principal Investigators: John C. Brandt  
 Malcolm B. Niedner, Jr.  
 Goddard Space Flight Center  
 Greenbelt, MD 20771

The largest-scale structures of comets--their tails--are extremely interesting from a physical point of view, and some of their properties are among the most spectacular displayed by comets. Because the tail(s) is an important component part of a comet, the Large-Scale Phenomena (L-SP) Discipline was created as one of eight different observational methods in which Halley data would be encouraged and collected from all around the world under the auspices of the International Halley Watch (IHW). The L-SP Discipline Specialist (DS) Team resides at NASA/Goddard Space Flight Center under the leadership of John C. Brandt, Malcolm B. Niedner, and their team of image-processing and computer specialists; Jurgen Rahe at NASA Headquarters completes the formal DS science staff.

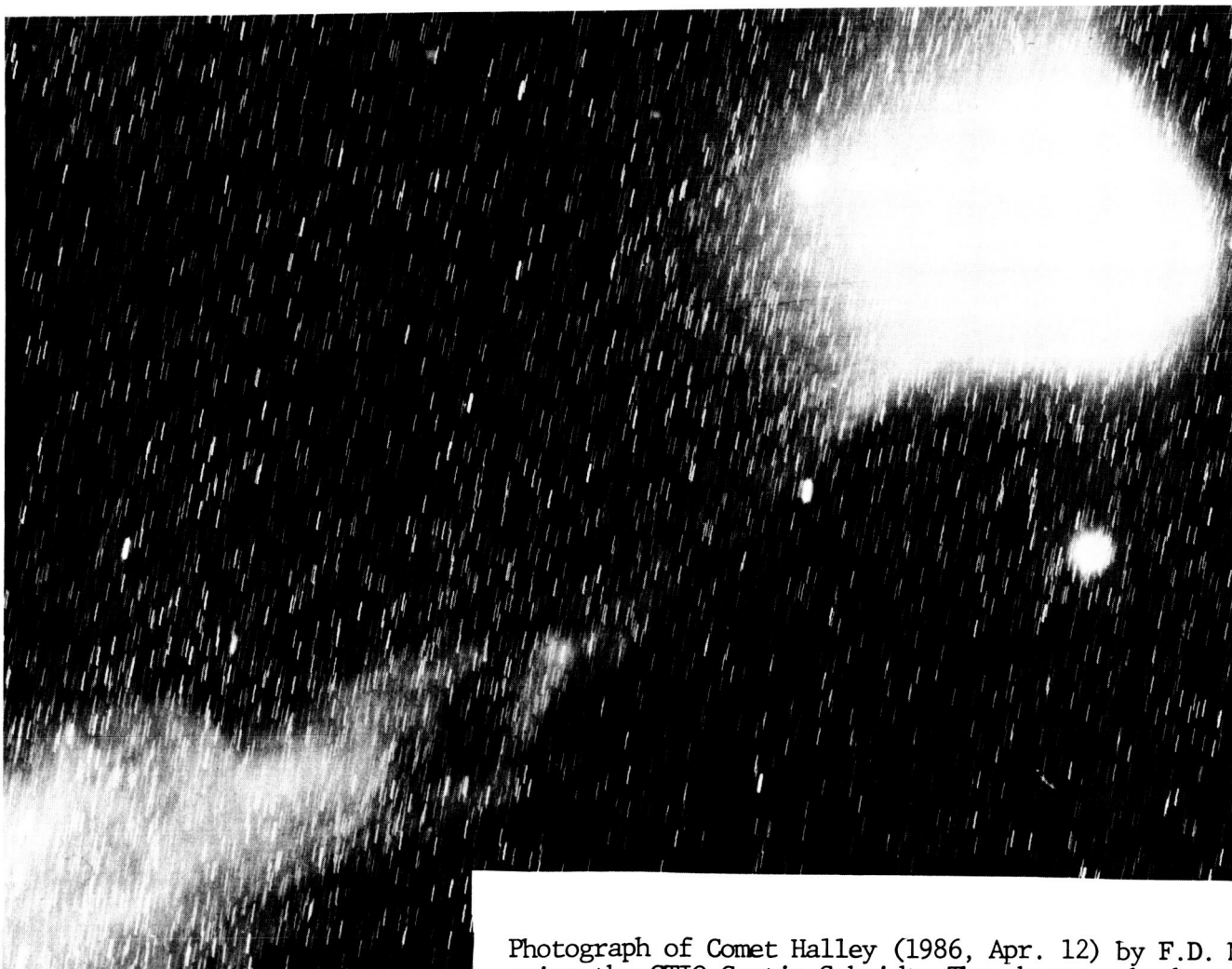
Since 1981, when the Discipline Specialist selections were made, we have been intensively active in recruiting the support of astronomers and observatories around the world in an effort to obtain the best photographic record ever of a bright comet. The specific type of data utilized in studies of Large-Scale Phenomena is wide-field images with fields of view (FOV) of 5° or more. Such images are typically photographic glass plates obtained with fast Schmidt cameras, or, almost as common, somewhat slower astrographic cameras with comparably large FOV's. The result of contacting astronomers globally has been the formation of an impressive L-SP Network consisting of some 105 different sites as well-scattered in longitude and latitude as the presence of land masses permits (however, see the description of the "Island Network" below). Over 35 different countries are represented in the network.

The plasma tail is one of two tail types exhibited by many comets (Halley among them), the other consisting of fine dust grains. In contrast, the plasma tail is composed of molecular ions such as  $\text{CO}^+$ ,  $\text{CO}_2^+$ , and  $\text{H}_2\text{O}^+$ , spiraling down magnetic field lines which have been captured by the comet from the solar wind and folded around in the approximate anti-solar direction into a tail configuration. Plasma tails "glow" and can be photographed because of the tendency of the ions to fluoresce in sunlight. Whereas dust tails are relatively stable on timescales of days to weeks, plasma tails are rarely steady in overall structure for more than a day. At intervals of approximately one week, the comet sheds its plasma tail completely in what is known as a "Disconnection Event" (DE), and proceeds to grow a new plasma tail. The details of this process are not clear, but what seems to be the basic cause is the crossing (by the comet) of reversals in the direction of the solar-wind magnetic field, and the consequent severing of the magnetic fields stored in the head region which had been the roots of the existing tail. If this model is correct, then not only is the DE seen to be a spectacular manifestation of the comet/solar-wind interaction, but comets (DE's) can be used to probe the structure of the solar wind well out of the plane of the earth's orbit, i.e., where spacecraft cannot travel.

The L-SP Discipline Specialist Team has adopted the study of DE's as perhaps its principal science target, and it is because of the rapid changes which occur in connection with DE's that such extensive global coverage was deemed necessary to assemble a complete record (with which the changes could be intelligently followed). However, a problem was recognized several years ago with respect to coverage. The comet would be brightest and presumably most active during 1986 March-April, when the comet would be far down in

southern skies and would not be visible to the majority of the northern hemisphere observatories. To at least partly offset this negative effect, an "Island Network" of small portable Schmidt cameras was set up to photograph the comet at remote island and other locations, and hence fill in the coverage gaps. Telescopes were placed on Tahiti, Easter Island, British Antarctica, South Africa, and Reunion Island (in the S. Indian Ocean), and volunteers were found to obtain the observations. All indications are that the Island Network was remarkably successful as over 600 images were obtained during the months March-April. Already, the images are being used to support the scientists working to interpret the data returned by the Halley encounter spacecraft. Some 20 DE's have been seen in the island and regular network imagery.

In addition to carrying out scientific studies, the team of personnel at NASA/GSFC is busy archiving the incoming worldwide images for eventual submission to the IHW Halley Archive at the Jet Propulsion Laboratory. This process starts with digitizing the images which arrive in either glass plate or film copy form. Once the images have been converted to digital format, they can be transformed to a standard angular scale, contrast-enhanced, be made into a movie, or manipulated using any number of other computer image-processing techniques. Early indications are that some 5,000-10,000 total images might have been obtained by the Large-Scale Phenomena Network, which should keep the L-SP Team busy for years both in archiving and in interpreting the data.



Photograph of Comet Halley (1986, Apr. 12) by F.D. Miller using the CTIO Curtis Schmidt. The photograph shows a spectacular disconnection event.

INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR RADIO SCIENCE

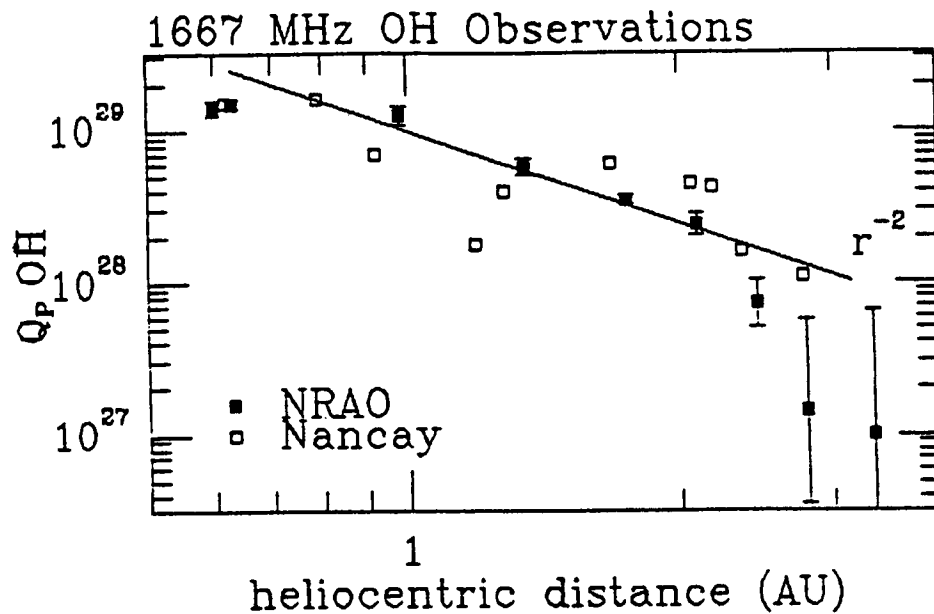
Principal Investigator: William M. Irvine  
Five College Radio Astronomy Observatory  
University of Massachusetts  
Amherst, MA 01003

Co-Investigators: F. P. Schloerb  
E. Gerard  
R. D. Brown  
P. Godfrey

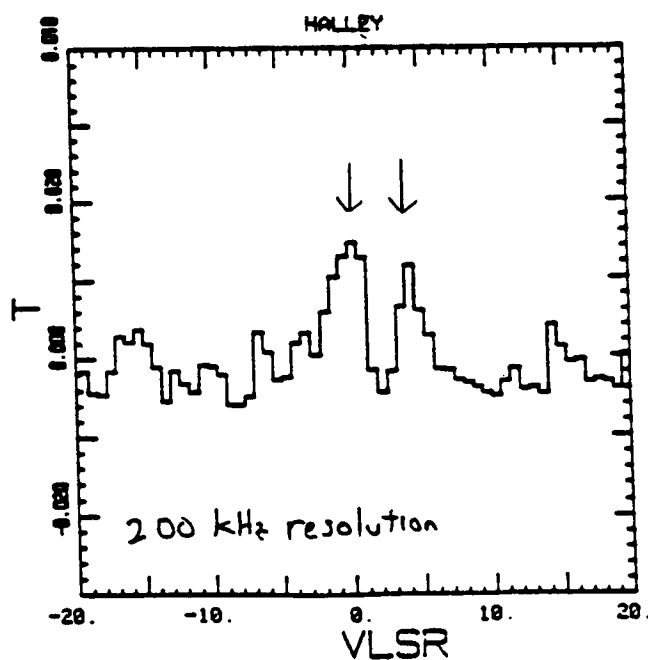
a. OBJECTIVES: The goals of the Radio Science Net of the IHW are to encourage radio astronomers to observe comet P/Halley using all available techniques, to assist such observations by rapid dissemination of relevant information including ephemerides, and to archive the data so obtained. Radio science is particularly able to provide certain types of information that are very hard to obtain by other ground-based techniques: measurement of the nuclear size, rotation, and roughness using radar techniques; observations of the presence and abundance of parent molecules in the coma from their rotational transitions; measurements of the OH ground state  $\Lambda$  doublet in order to provide information on the gas production by the comet, on kinematics in the coma, on coma asymmetry as possibly related to out-gassing events, and potentially on the cometary magnetic field via the Zeeman effect; of large particles in the coma from their thermal emission and on effects via nonthermal emission; and possibly on electron densities and magnetic fields associated with the comet from occultation of background radio sources.

b. ACCOMPLISHMENTS: Some 34 radio observatories in 18 countries are participating in the Radio Science Net of the International Halley Watch. Approximately 100 radio astronomers are contributing to this effort, which has included observations of comets P/Crommelin and P/Giacobini-Zinner as well as P/Halley. It is clear that the record of data for the 18 cm OH ground state  $\lambda$  doublet, which provides fundamental information on the gas production rate, kinematics, and potentially the magnetic field in the coma, will be vastly more complete and of higher accuracy than has ever been obtained on any previous comet. The coverage by a number of radio observatories will enable short period variations to be studied and correlated with simultaneous data obtained at other wavelengths. Like wise, the first definitive detection of the important parent molecule hydrogen cyanide in a comet has been obtained and is being studied by groups in the United States, Sweden, and France. The first detection of the comet with the Very Large Array telescope operated by NRAO has been achieved and has produced exciting results for the distribution of emission at high angular resolution from the OH radical. At this writing data are still being obtained and being processed, and there are still strong indications that exciting information will be obtained from radar studies of P/Halley and from searches for additional parent molecules.

c. PROPOSED RESEARCH: The next year will involve a major effort to collect the data obtained during the apparition of P/Halley and that of P/Giacobini-Zinner and place it in a consistent form for inclusion in the IHW archive.



Production rate of OH in P/Halley as measured by Schloerb and Claussen at NRAO and Gerard et al. at Nancay.



Detection of HCN in P/Halley by Schloerb et al. at the FCRAO 14 m antenna. Two hyperfine components are visible.

## INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR INFRARED SPECTROSCOPY AND RADIOMETRY

Principal Investigator: Roger F. Knacke  
Earth and Space Science Department  
State University of New York  
Stony Brook, NY 11794

Co-Investigators: T. Encrenaz

**Abstract:** The Infrared Net has been active in all areas of comet science in its domain. The more than 100 members of the net and 30 participating observatories are still engaged in observations, and only a preliminary discussion of the highlights of the program is possible at this time.

### Photometry

We have had reports from the Comet Halley photometric monitoring programs of Bertre, Epchtein, and Encrenaz (ESO), Gregory and Matsuura (CTIO), Hanner and Tokunaga (JRTF), Moneti and Stanga (TIRGO), and Whitelock (SAAO). Other groups are making photometric observations but have not yet reported. The IRTF results are being made available on the Arizona State Hotline and the IAU telegrams on a monthly basis.

Some preliminary impressions of the data suggest that the near infrared colors resemble those of other comets. Early estimates of the mass loss rate based on IRTF results give  $2-4 \times 10^5 \text{ gms}^{-1}$  of dust near the beginning of October. If confirmed, this would suggest a higher dust to gas ratio than estimated from visual measurements.

### Spectroscopy

Several intermediate resolution measurements have been made. Bregman, Whitteborn, Rank, and Wooden found an absorption feature at 3.1 microns which they attribute to water ice. Brooke, Geballe, Knacke, Noll, and Tokunaga reported detection of water vapor emission at 1.4 and 1.9 microns. The near infrared continuum has the red shape observed in the dust continuum of other comets. Crovisier, Mailland, Encrenaz, and Combes obtained 0.8 - 2.6 in FTS spectra which show CN bands and probably  $\text{H}_2\text{O}$ .

### Airborne

The KAO was grounded for repairs in November, but flights to observe Comet Halley are scheduled for the next several months. Russell (Aerospace Corp.) and Campins (Planetary Sciences Institute) are planning observations from the Lear Jet. M. Mumma and collaborators detected several water lines in high resolution FTS spectra of the coma of Comet Halley. Variable water production rates are suggested. More observations are planned in March and April 1986 flights.

### Imaging

Telesco, Baugher, Decker, Campins, Thronson, and Mozurkewich obtained remarkable 10 micron images of Comet Giacobini-Zinner with an array at the Wyoming Observatory. They observed Comet Halley at the IRTF and have recently released these images. Joyce and Gallagher obtained the first (to our knowledge) 1.6 micron (H) images of Comet Halley at Kitt Peak. A number of groups plan imagings in the post-perihelion period, including ones around the spacecraft encounters in March. These observations are the beginning of imaging science applied to comets in the infrared region of the spectrum. They hold great promise for improving our understanding of coma and tail physics and composition.

INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR  
NEAR-NUCLEUS STUDIES

Principal Investigator: Stephen Larson  
Lunar and Planetary Laboratory  
University of Arizona  
Tucson, AZ 85721

Co-Investigators: Zdenek Sekanina, Jurgen Rahe

The purpose of the Near-Nucleus Studies Net is to study the processes taking place in the near-nucleus environment as they relate to the nature of the nucleus. This is accomplished by measuring the spatial and temporal distribution of dust, gasses and ions in the coma on high resolution images taken from many observatories around the world. By modeling the motions of discrete dust features in Comet Halley, it is often possible to determine the locations of the emission sources on the surface and learn about the nucleus structure. In addition to the general goals shared by all IHW nets, the scientific goals of the net has been to determine 1) the gross surface structure of the nucleus, 2) the nucleus spin vector, 3) the distribution and evolution of jet sources and 3) the interrelationships between the gas, dust and ion components of the coma. An additional "Comet Giacobini-Zinner Watch" was carried out by the NNSN in support of the NASA International Cometary Explorer flyby.

Several hundred images of P/Giacobini-Zinner were taken by NNSN members concentrated during the week centered on the ICE encounter on Sept. 11, 1985. The relatively weak and essentially uniform distribution of dust recorded by the NNSN was consistent with the low dust impact rate detected by ICE. Correlation of the ion distribution from ICE and high resolution groundbased images is underway.

The analysis of over 55 coma features in 35 digitally processed images of P/Halley taken in 1910 produced a map showing a non-uniform distribution of dust jet sources on the nucleus and a 52 hour rotation period (IAUC 4151). NNSN CCD data from the current apparition confirmed the roughly two day modulation in jet activity. One week before the first spacecraft encounter, we communicated to the flight project centers in Moscow and Darmstadt that the phasing of jet activity observed from the ground predicted greater jet activity for the Vega 1 encounter than for

Vega 2 and Giotto. NNSN observers were able to record the jet that the Vega 1 spacecraft flew through as well as the other jets imaged by spacecraft cameras. Detailed analysis and comparison between NNSN and spacecraft images will provide essential calibration of the modeling of jets observed throughout the apparition. So far, over 4000 images are known to exist from observatories in Chile, Arizona, Hawaii, Australia, China, South Africa and Spain, and we expect to hear from others in the next few months. One important key to the success of the NNSN was the last minute construction of two portable CCD cameras used by the Univ. of Arizona and Univ. of Maryland in Arizona, Hawaii, Australia and South Africa. The instruments were fully operational just as jet activity commenced in November, 1985, and since then have been used almost nightly.

Collection, reduction, reformatting and printing of the images for the archive has begun so that the archive deadline can be met. Enhancement, measurement and analysis the images will take several years to complete. For the first time it will be possible to produce a detailed map of active areas and their changes over the comet's most active six months.

#### Publications:

Larson, S.M. and Sekanina, Z, (1985) Coma Morphology and Dust-Emission Pattern of Periodic Comet Halley.III. Additional High Resolution Images Taken in 1910. ASTRON. J.,90, pp 823-826, 917,923.

Larson, S.M. (1986) A Review of Some Digital Image Processing in Cometary Research, in "Asteriods, Comets and Meteors II", ed. C.-I. Lagerkvist. pp 449-460.

Sekanina, Z. and Larson, S.M.,(1986) Coma Morphology and Dust-Emission Pattern of Periodic Comet Halley.IV. Spin Vector Refinement and Map of Discrete Dust Sources. (submitted to ASTRON.J.)

Sekanina, Z. and Larson, S.M.,(1986) Dust Jets in Comet Halley During the Encounters. (submitted to NATURE)



INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR  
SPECTROSCOPY AND SPECTROPHOTOMETRY

Principal Investigator: Susan Wyckoff  
 Physics Department  
 Arizona State University  
 Tempe, AZ 85287

Co-Investigators: M. C. Feston, P. Wehinger

**Objectives:** The goals are to coordinate spectroscopic observations of Comets P/Crommelin, P/Giacobini-Zinner and P/Halley, to communicate preliminary results to the astronomical community, and to archive the data collected from observers throughout the world. The ASU IHW Center has the additional responsibility of maintaining the IHW Electronic Bulletin Board which reports real-time information on the status of Comet P/Halley. Access to this electronic bulletin board via telephone modem connection is available to any astronomer upon request.

**Accomplishments:**

- The P/Crommelin archive has been published.
- P/Giacobini-Zinner data are being consolidated and archived.
- Spectroscopic observations of P/Halley have been obtained since 1984.
- Data collection by members of the spectroscopic network throughout the world reached peak activity in March 1986.

Observers in India, Australia, Chile, Japan, France, Great Britain, Federal Republic of Germany, Spain, South Africa and the United States have been reporting spectroscopic observations of P/Halley to the ASU Center, and accessing the IHW Electronic Bulletin Board. The ASU Center received an average of 10 reports each day in March 1986, while an average of 30 astronomers daily read the IHW Bulletin Board during this month. Regular communication is maintained with our Co-Discipline Specialist, M. Festou, in France via the ASU IHW Mail Facility and Bitnet.

Observations reported by net members to the ASU Center include:

- All neutral and ionic molecular species previously observed in other comets have been observed in P/Halley. Several weak unidentified features have been found. The C(<sup>1</sup>D) line has been detected in the near infrared.
- Variability in production rates of water dissociation product OH on timescales of days (i.e. approximate rotation period of nucleus).
- Variability of smaller amplitude in production rates of trace molecular species on timescale of days.
- Large variations in ion production rates on timescales of days.
- Different methods of determining water production rates differ by factors greater than variability, perhaps attributable in part to optical depth effects.
- High resolution spectroscopic data to determine the isotope abundance ratios <sup>13</sup>C/<sup>12</sup>C and H/D and to measure the [OI] 5577 Å and 6300 Å fluxes have been obtained.
- Fabry-Perot velocity measurements of molecular ions during a tail disconnection event have been obtained.

Programs for reading and writing FITS formatted data files have been developed and are available by request from the ASU Center to astronomers from any discipline.

Spectroscopic data on comets P/Crommelin, P/Giacobini-Zinner and P/Halley have been obtained by the ASU comet group using telescopes in Arizona, Australia and Chile during the past two years.

A brochure about comets in general and Comet Halley in particular funded by ASU for distribution to the public was produced in October 1985. By March 1986 56,000 copies had been requested by the interested lay public in the state of Arizona. This response is representative of the magnitude of the public inquiries which the ASU IHW Office handled during that six month interval.

#### Publications:

"Report on the Spectroscopy and Spectrophotometry Center", in International Halley Watch Newsletter No. 6, 33, 1985.

"Report on the Spectroscopy and Spectrophotometry Center", in International Halley Watch Newsletter No. 7, 24, 1985.

"The Halley Hotline: An Electronic Bulletin Board", in International Halley Watch Newsletter No. 8, 28, 1986.

"Guide to Using the IHW FITS Read and Write Programs", ASU Special Publication No. 1, 1985.

"Halley's Comet: A Guide for Arizona Viewers (1985-6)", ASU Special Publication No. 2, 1985.

INTERNATIONAL HALLEY WATCH: DISCIPLINE SPECIALISTS FOR ASTROMETRY

Principal Investigator: Donald K. Yeomans  
 Jet Propulsion Laboratory  
 California Institute of Technology  
 Pasadena, CA 91109

Co-Investigators: Richard West, Robert Harrington, Brian Marsden

a. Objectives: The Astrometry Network of the International Halley Watch (IHW) has organized and coordinated more than 300 astrometric observers from 47 countries in an effort to provide for accurate positional information on comets Halley and Giacobini-Zinner. This information is being used to constantly update the existing orbits and ephemerides for the various flight projects to these two comets and also for the other ground-based observers within the IHW organization. The astrometric data, as well as the resultant orbits and ephemerides, are being distributed to all requesting observers and they will be cataloged within the general IHW archive system.

b. Accomplishments: As of mid-March 1986, there were nearly 4500 astrometric observations (from 121 observatories) reported to the Astrometry Network orbit determination center at the Jet Propulsion Laboratory. Over 90% of these observations were accurate enough to be used in the orbit determination solutions for comets Halley and Giacobini-Zinner. The Astrometry Network conducted a workshop on modern astrometric observing techniques and data reduction procedures and the proceedings from this workshop were distributed to Network members for their reference. Special Comet Halley and Giacobini-Zinner reference star catalogs were compiled and distributed to Net members for their use in data reduction and in the case of comet Halley, many of the catalog star positions were re-observed and remeasured providing a vast improvement over the existing catalogs. Special reference star catalogs, data reduction programs and ephemeris generation programs were distributed to Network members to ensure consistency in the astrometric data. In addition, all the 1835-36 and 1909-11 astrometric data were re-reduced with respect to modern reference star catalogs (and in some cases the old plates were re-measured). The success of the Astrometry Network's efforts can be measured by the accurate targeting of the ICE spacecraft through the narrow central portion (neutral sheet) of that comet's ion tail and the accurate targeting of the Giotto spacecraft to within 605 km of comet Halley's nucleus.

c. Proposed Research: During FY86 and FY87, continuing astrometric data will be used to update the orbits of comets Halley and Giacobini-Zinner. Efforts will be made to include spacecraft-comet angle data in the orbit solutions and the obvious center of light/center of mass offset seen in the post-perihelion observations of comet Halley will be used to determine the magnitude and functional form of this offset with changing heliocentric distance. Data archiving will begin for both comets Halley and Giacobini-Zinner.

d. Publications:

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 June 18-19, 1984 at the European Southern Observatory, JPL  
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VIII. PUBLICATIONS

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